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THE GENERAL ELECTRIC CO. LTD. OF ENGLAND

G.E.C. 25 kV Electric Locomotive
(See page 71)

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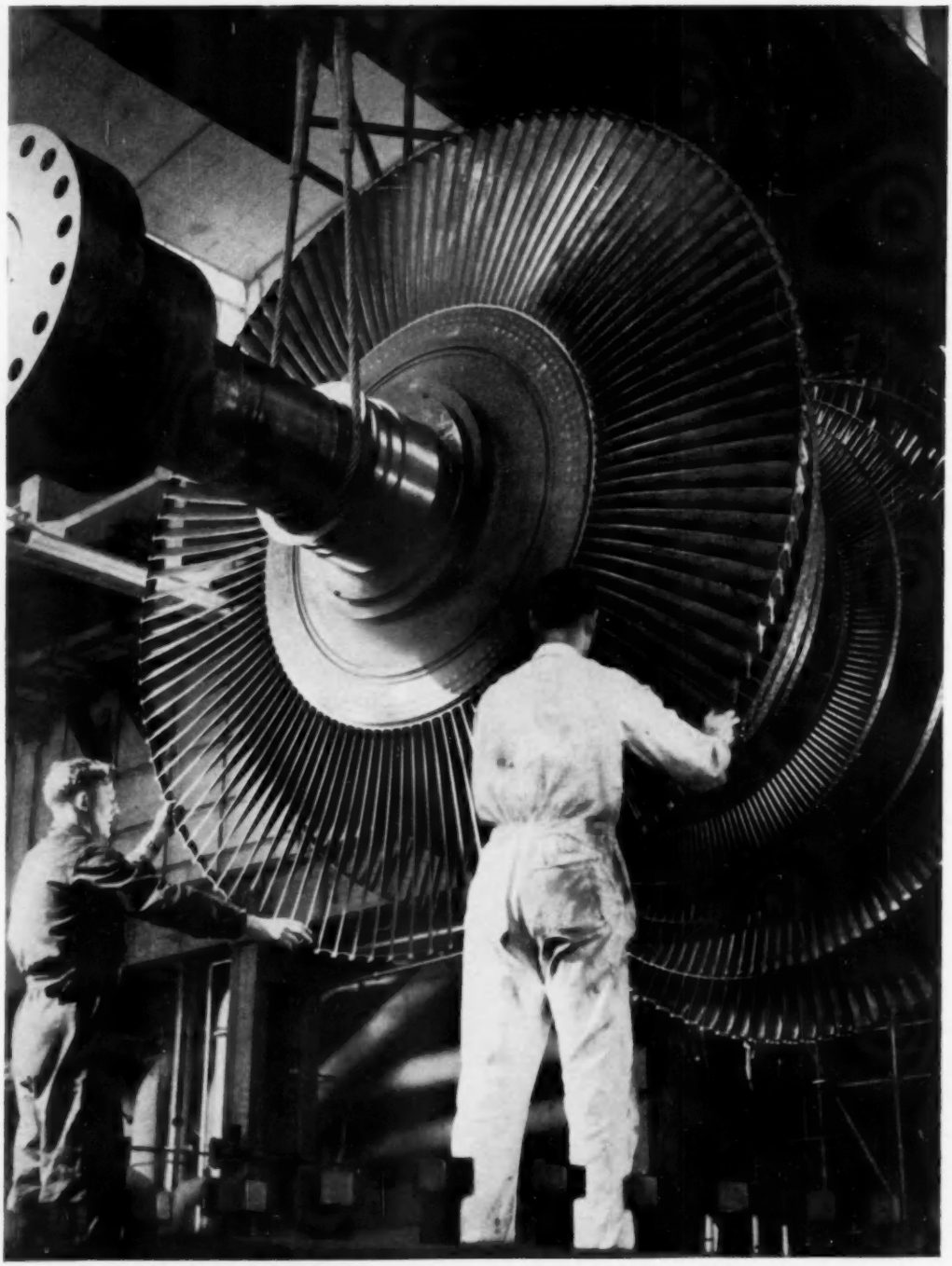
**COVER PICTURE**

*G.E.C. 25 kV a.c. Electric Locomotive in service on the London Midland Region of British Railways. These locomotives have a continuous rating of 3300 h.p. and are capable of speeds of up to 100 miles per hour.*



*120 MW steam turbine under erection at the Northfleet Generating Station of the Central Electricity Generating Board.*

# The 'Consort' Nuclear Research Reactor

By K. HART, A.M.I.Mech.E., Atomic Energy Division.

A NEW low-priced design of nuclear research reactor is to be marketed by G.E.C. This reactor, 'Consort', is one of an inherently safe type, using ordinary water as both moderator and coolant. It has been designed jointly by the G.E.C.-Simon-Carves Atomic Energy Group and the nuclear power group at the Imperial College of Science and Technology, London University. This collaborative approach has resulted in a design particularly suitable to meet the specialized research and training requirements of universities and colleges in any part of the world. At the present time 'Consort I' is the only completely British designed research reactor in the 10 kW range. The 'Consort II' version is similar in design but has the control and instrumentation, cooling circuits and shielding designed to allow of continuous operation up to and including 100 kilowatt power output, with additional facilities for the production of radio isotopes.

The design was originally produced for the proposed installation to be operated by the nuclear power group of Imperial College, under the leadership of Professor J. M. Kay, at a convenient site outside London. This proposal, which is an integral part of the College's programme for the expansion of its nuclear engineering training and research facilities, has been approved in principle but at present awaits financial sanction before an order can be placed.

The new reactor was designed with a view to combining some of the principal advantages of the two well-known existing types of water-moderated research reactors, the 'swimming-pool' type and the 'enclosed-tank' type. In the former design, the reactor core is housed in a large tank of water at a substantial depth below the surface so that the water itself provides all the shielding necessary above the core. This arrangement offers the advantages of good accessibility and ease of handling of the fuel elements. The enclosed-tank reactor uses a comparatively small tank of water with concrete shielding above the core as well as round the sides. The whole assembly is more compact than the swimming-pool type with the result that it is much easier to locate external experimental assemblies close to the core itself. On the other hand, a relatively complex fuel-handling system is required.

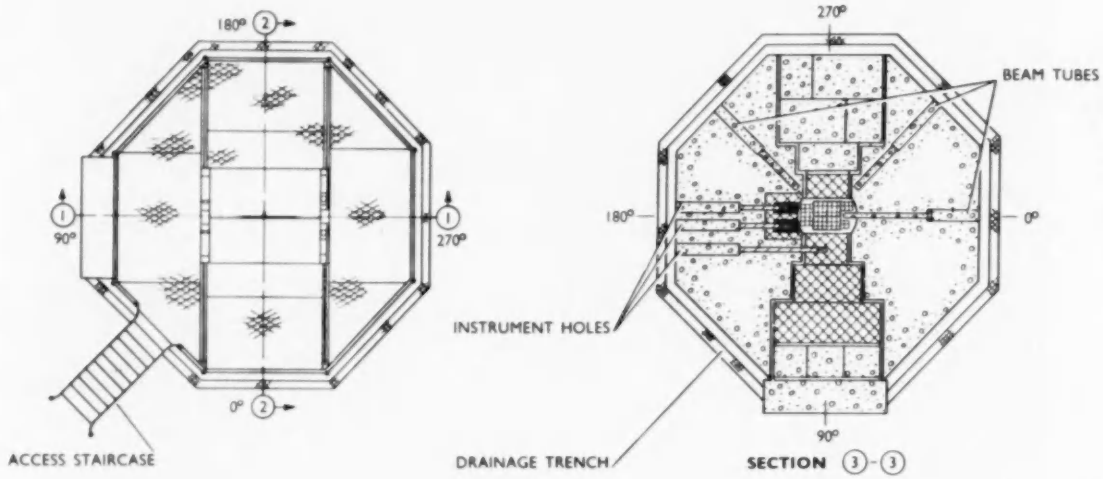
'Consort' provides a most effective compromise between these designs, combining ease of fuel-handling with compactness and good accessibility to the core for experimental facilities. The core is located only 10 feet below the surface of the water moderator in an open-topped tank but additional shielding is provided in the form of movable concrete-filled trolleys which cover the top of the tank while the reactor is in operation. It has been possible to incorporate an experimental 'bare face', protected by portable shielding blocks, very near the reactor core, a most important facility for research and training purposes. When the reactor is shut down, the shielding trolleys can be withdrawn and manipulation of the fuel elements can then be carried out beneath the water, under direct observation by the operator using simple manual techniques. Furthermore, the whole design is based on the use of a well-proved type of enriched-uranium-alloy fuel element which is readily obtainable from the United Kingdom Atomic Energy Authority as a standard production item.

## BASIC DESIGN FEATURES.

### Experimental Facilities.

The new reactor has been designed primarily as a source of neutrons for use in experimental work for research and training purposes. The rating of the Imperial College design for continuous operation is 10 kW and, at this power level, a flux of approximately $3\times10^{10}$ thermal neutrons and $2\times10^{10}$ fast neutrons/cm$^2$ sec is available at an experimental face in the wall of the reactor tank adjacent to the core. A similar flux can also be obtained at the inner face of a graphite thermal column on the opposite side of the tank.

The bare experimental face is a particularly versatile facility. It allows experimental assemblies to be built very close to the reactor core, thus providing them with a high neutron input. If it is desired to feed a vertical beam of neutrons to an experimental assembly, as may be convenient with water-moderated systems, this can be achieved by means of a dual-purpose thermal column, available as an optional extra. This consists of a horizontal column of graphite built against the bare face and having a vertical stub at its outer end. By means of suitable voids in the graphite the neutron flux at the end of the stub may be optimized for both strength and distribution. The dual-purpose column



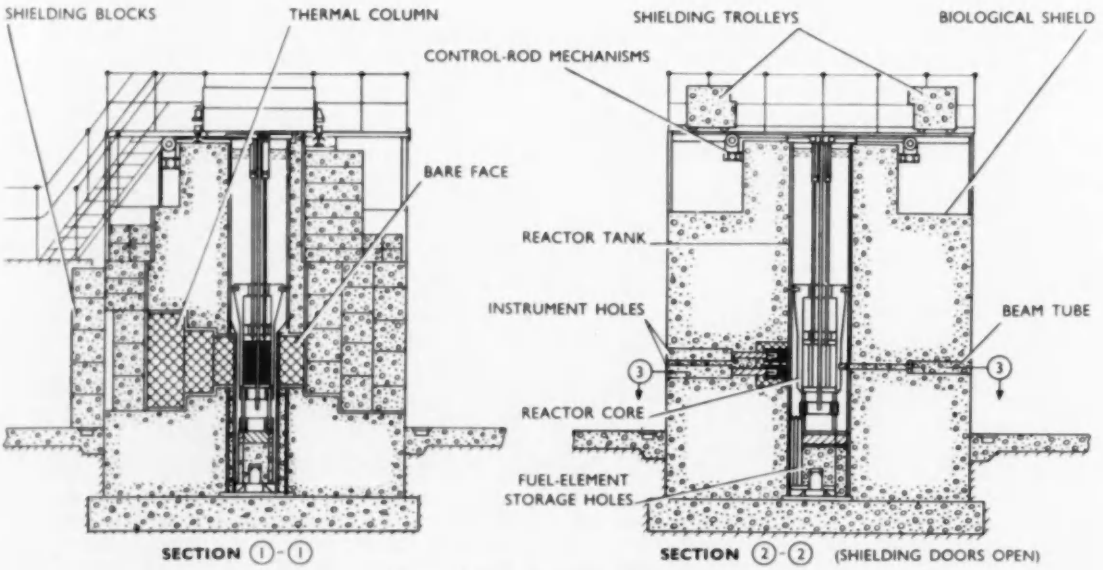
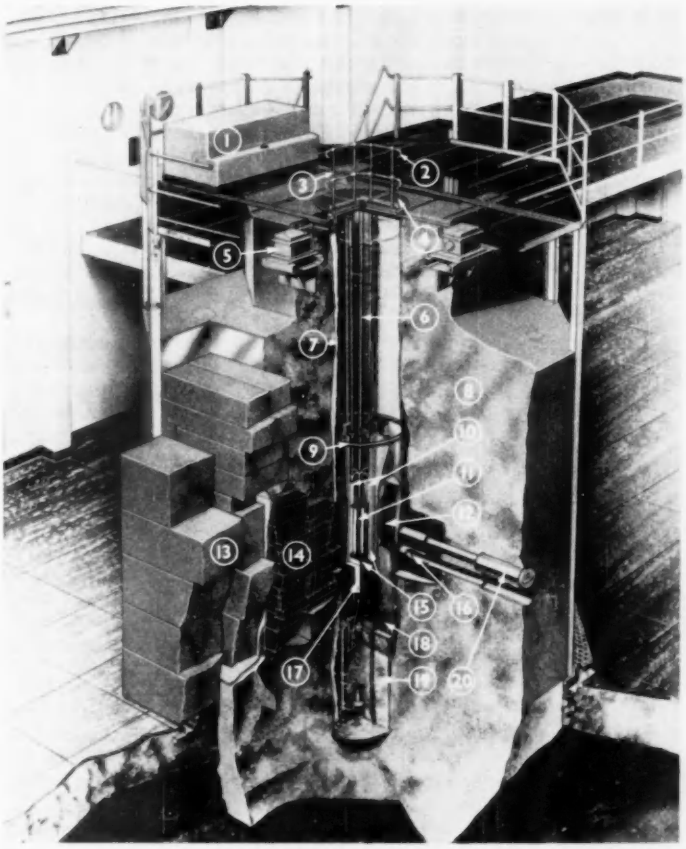




*Fig. 1.—Sectional drawings of the reactor.*



**KEY.**

1. *Shielding Trolleys (one only shown).*
2. *Safety Handrail for fuel handling.*
3. *Pipe Duct.*
4. *Removable Tank Covers.*
5. *Neutron Absorbing Rods—drive mechanisms.*
6. *Experimental Tube.*
7. *Reactor Tank.*
8. *Biological Shield.*
9. *Cooling Water Outlet Ring Main.*
10. *Neutron Absorbing Rods.*
11. *Fuel-elements.*
12. *Bare Face Graphite.*
13. *Removable Concrete Shielding Blocks.*
14. *Thermal Column Graphite.*
15. *Core Supporting Plate and Guide Structure.*
16. *Flux Measuring Instruments.*
17. *Intermediate Structure.*
18. *Shielding Plugs.*
19. *Fuel-element Storage Structure.*
20. *Instrument Shielding Plugs.*

*Fig. 2.—A sectioned impression of the 'Consort I' nuclear research reactor.*

may at the same time be used to provide a horizontal beam of neutrons if required.

Other experimental facilities can be provided in the form of one or more beam tubes issuing radially from the reactor tank at core level, while a vertical tube through the centre of the reactor core permits the cycling of specimens into and out of the central flux of $4 \times 10^{11}$ fast and $2 \times 10^{11}$ thermal neutrons/cm$^2$ sec.

### Reactor Core.

The core of the reactor is built up from between 20 and 24 fuel elements of the standard M.T.R. type in which the enriched uranium-aluminium-alloy fuel is fabricated in the form of slightly curved plates clad in aluminium. A number of these plates are assembled to form an approximately square-sectioned element so that the coolant can flow between the faces of adjacent plates.

The fuel elements are arranged vertically to form an approximately cylindrical core, each element being located at its lower end by a spigot which engages in a hole in an aluminium support plate. A hole through the spigot permits the water coolant to flow upwards between the fuel plates.

Below the level of the core within the reactor tank, shielded fuel-element storage holes are provided, each fitted with a removable stainless-steel shielding plug. These compartments can accommodate a full charge of 24 fuel elements. The design of the storage area is such that there is no possibility of inadvertently assembling a critical mass of fuel. The shielding of the holes is adequate to permit direct access to the experimental face and the thermal column one day after the reactor has been shut down.

### Reactor Structure.

The core, with its support structure, is mounted near the bottom of a vertical cylindrical tank filled with water to act as moderator, coolant and shield. The tank, which is made of high-purity aluminium, $\frac{3}{8}$ in. thick, is open at the top, but a Perspex cover keeps the water surface free of dust. Provision is made for the dispersal of hydrogen evolved in the moderator during operation of the reactor and also for the detection and

collection of fission products in the event of a fuel-element failure.

In the vicinity of the core, two rectangular flat surfaces are provided in opposite walls of the tank to accommodate the experimental face and the thermal column. At the same level, the beam tubes project into the tank through tube stubs which are welded to the tank wall and blanked off at their inner ends.

The tank is surrounded by a concrete biological shield, octagonal in plan, with a thickness of approximately 7 ft 6 in. reducing to 3 ft near the top of the tank. The main body of this shield is a monolithic structure, but on two diametrically opposite faces, removable concrete blocks are employed so as to permit the necessary flexibility in the disposition of shielding around experimental assemblies set up adjacent to the experimental face and the thermal column. This arrangement also provides a means of access to the experimental facilities after the reactor has been shut down. It is important to ensure that such access is not prevented by the presence of dangerously high levels of radiation arising from neutron-activation of the concrete, and for this reason a sheet of cadmium is interposed between the concrete and the tank wall in the vicinity of the experimental facilities. The activation of steel structural members in this area is also reduced by the application of a cadmium coating.

Axial shielding above the core consists of an 11 ft 6 in. depth of water which is supplemented, while the reactor is in operation, by a 2 ft thickness of concrete. This concrete shielding takes the form of two movable trolleys which run on guides set in the top face of the reactor structure, the joint between the trolleys being stepped and shaped to fit around the control-rod support tubes. The trolleys are moved by hand, and interlock limit switches are fitted both at the fully open and at the closed position.

### Control and Instrumentation.

The reactor is controlled by means of vertical neutron-absorbing rods which are of flat section and pass through guide tubes between adjacent fuel elements. There are two shut-down rods, one fine control rod and one safety rod.

Two alternative types of control-rod mechanisms are available for this reactor. In one design, the shut-down and fine control rods are each supported by a stainless steel tape which passes over a pulley vertically above the rod and is then attached to a driving pulley mounted at the edge of the biological shield. This pulley is driven by a small geared motor through an electromagnetic clutch which, under 'scram' conditions, is automatically released so that the rod falls into the core. The safety rod, which is held normally in the out position by means of an electromagnet fitted vertically above the rod, is arranged to fall rapidly into the core by interruption of the current to the supporting electromagnet. A built-in device allows for manual re-setting of the rod; this can be performed only when the fault has been cleared. An interesting feature incorporated in this system is the water dashpots which absorb the energy of the falling rods following emergency release.

In the alternative arrangement, the upper end of each rod is coupled, by means of an electromagnet, to a vertical rack moving between guide rollers. The rack is driven by a squirrel-cage induction motor through a gear train from which the drive to the Magslip rod-position indicator is also taken. If an emergency should arise, the electromagnets are automatically de-energized, thus releasing the rods from the racks and allowing them to fall into the core under gravity.

The instruments required for the measurement of flux and other control functions are mounted in shielded holes close to the wall of the reactor tank, the necessary connexions being carried in tubes passing through the biological shield. The control equipment and instrumentation needed for operation of the reactor are housed in panels in a separate control room.

### Fuel Handling.

The fuel-handling arrangements are such that, once the reactor has been shut down and the shielding trolleys withdrawn, fuel elements can be transferred between the core and the storage holes in complete safety by means of a simple manual operation. The handling tool consists of a long tube with a grab-head at its lower end and release levers at the top. The jaws of the grab are shaped so that an element cannot be released until its weight is fully supported either in one of the storage holes or by the core-support plate. Furthermore, the tool is designed to limit the height to which an element can be raised above the core, thus ensuring that the operator is always shielded from radiation by an adequate depth of water.

### Water Circuit.

The water connexions to the reactor, comprising inlet, outlet, and overflow pipes, enter the tank through the top.

On leaving the reactor, the water is pumped through an external circuit by means of a motor-driven pump capable of handling 400 gallons per hour. The main circuit includes filters for the removal of any entrained solid particles, and a cooler which is controlled to ensure that the water-temperature at inlet to the reactor core is kept at a steady value. The water is maintained at the required degree of purity by continually diverting 10% of the main flow through a water-treatment plant.

All the equipment associated with the water circuit is housed in a plant room adjacent to the reactor. A dump tank, installed below ground level in a shielded pit, is used for holding any active effluents from the water-treatment plant pending their disposal, and it can also, in an emergency, accept the whole of the water in the reactor circuit.

# 25 kV a.c. Electric Locomotives for British Railways

By W. D. MORTON, M.A. (CANTAB.), A.M.I.E.E., A.M.I.Mech.E., Manager, Traction Division.

*Fig. 1.—Sir Leslie Gamage, Chairman and Managing Director of The General Electric Company Limited, at the controls of a 3300 h.p. 25 kV electric locomotive for the London Midland Region of British Railways.*

THE first of ten 25 kV electric locomotives ordered from the G.E.C. is now in service on driver training on the London Midland Region of British Railways. The locomotives are designed for a wide range of passenger and goods duties including the haulage of 100 mile/h express passenger trains, and carry British Railways type A designation, the serial numbers being E3036-E3045 inclusive. Provision has been made for operation on both 25 kV and 6·25 kV, 50 c/s a.c. supplies.

The locomotives have been designed to the requirements of the British Transport Commission, under the general direction of Mr. S. B. Warder and Mr. J. F. Harrison, Chief Electrical Engineer and Chief Mechanical Engineer respectively of British Railways Central Staff.

The mechanical parts for these locomotives have been designed and built by North British Locomotive Company Ltd., as sub-contractors, and the specification requirement of a maximum axle load of 20 tons, using the Bo-Bo wheel arrangement, has been met with a comfortable margin, the overall weight of the first locomotive being below 77 tons. This has been achieved, using traditional materials, by very close attention to the structural and detail design for minimum weight of all major and minor components.

The locomotives have been designed to give the advantages of a duplex equipment. With the excep-

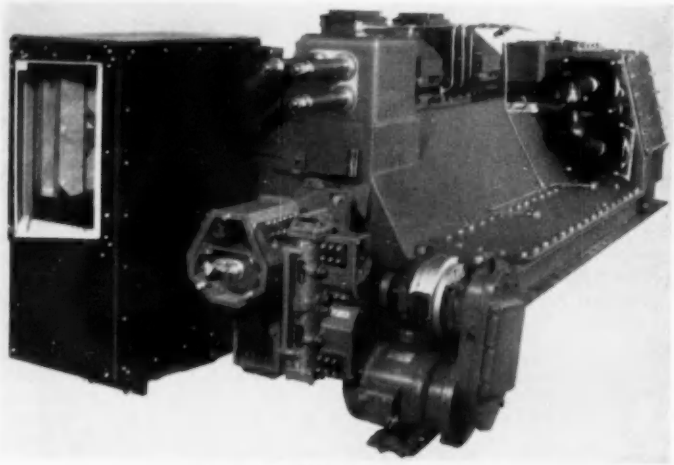


*Fig. 2.—The H.V. tap-changer unit.*

ion of the main transformer and its associated equipment, the unit can be divided into two virtually identical halves. In an emergency single traction motors can be isolated, and a complete bogie, with its auxiliary equipment, rectifiers, etc., can be cut out.

**PRINCIPAL DIMENSIONS AND DATA.**

| | |
|---|---|
| Wheel arrangement ... | Bo-Bo |
| Maximum speed ... | 100 mile/h |
| Continuous h.p. rating | 3300 |
| Maximum tractive effort ... ... | 50 000 lb |
| Tractive effort at continuous rating ... | 21 000 lb at 54 mile/h |
| Weight in working order ... ... | 76·5 tons |
| Length over buffers ... | 53 ft 6½ in. |
| Height over cab ... | 12 ft 4 7/16 in. |
| Maximum width ... | 8 ft 8¼ in. |
| Bogie wheelbase ... | 10 ft 0 in. |
| Bogie pivot centres ... | 29 ft 6 in. |
| Wheel diameter ... | 4 ft 0 in. |
| Radius of minimum curve ... ... | 4 chains |

**EQUIPMENT ARRANGEMENT.**[3]

The general layout of the equipment is shown in fig. 4. The high-voltage equipment is contained in a steel enclosure, one side of which forms the inner wall of the corridor connexion between the two cabs. The supply changeover switch and the motor-driven tapchanger (fig. 2) are mounted on top of the main transformer, which is centrally located and divides the H.V. compartment into two sections. Each of these sections contains one of the H.V. apparatus frames and one bank of rectifiers with secondary H.V. gear. These are symmetrically arranged about the transformer, access being obtained through doors from the corridor. One of the main equipment frames is shown in fig. 3 and a rectifier frame in fig. 5.

Machinery compartments, housing the M.G. blower sets and other auxiliary equipment, are located at each end of the locomotive between the cab vestibule and the H.V. compartment. At one end are mounted the two exhauster sets, a rack for the brake equipment control valves and a chemical toilet. The main air compressor is mounted at the other end, together with an auxiliary compressor which is normally used when preparing a locomotive for service, and which runs off the battery to provide sufficient air pressure to raise the pantograph and close the air-blast circuit breaker.

The access doors to the H.V. compartment are fully interlocked with the pantograph-raising and roof-earthing gear in such a way that they cannot be opened without first dropping the pantograph and earthing the circuit breaker. The pantograph cannot be raised until the doors are closed and locked. Batteries, weak-field resistors and air reservoirs are carried under the main frame between the bogies. The principal runs of cable are carried in a duct below the corridor floor.

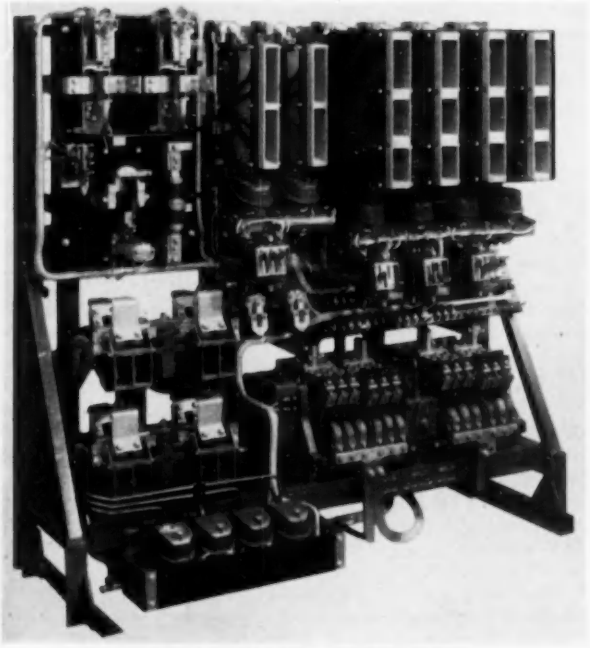


*Fig. 3.—One of the main equipment frames.*

*Fig. 5.—Rectifier frame showing ' Com-Pak ' rectifier units.*

With the cathode-spot stability and efficient cooling provided, it has been possible to produce a rectifier of much smaller dimensions than those of conventional rectifiers of the same output. In the ' Com-Pak ' rectifier the arc path is shorter, the voltage drop is lower and consequently the efficiency is higher. Special mercury anti-swill features are incorporated to make the unit suitable for use in a vehicle subject to vibration, impact shocks and other random movements, and extended tests in railway vehicles under varying service conditions have demonstrated its suitability for this purpose.

The main transformer is of the oil-cooled type in which the oil is rapidly circulated through a radiator by a motor-driven pump. The three-limbed core has windings on the outer limbs only, the centre limb acting as a common return path for the magnetic flux. In order to reduce weight, the core clamps are extended to form mounting feet which take the whole of the core weight. This enables a light oil-tank to be used, as it is required to support only the weight of the oil. The mounting feet are arranged in the plane of the centre of gravity of the transformer, to eliminate any overturning moment under conditions of buffing shock.

**CURRENT COLLECTION AND CONVERSION.**

Current is collected from the overhead line by one of the two Stone-Faiveley pantographs, feeding through a Brown-Boveri air-blast circuit breaker to the supply changeover switch. This is an off-load switch operating under the control of automatic voltage detection and selection equipment to give the correct transformer tapping for running on a line voltage of 25 kV or 6·25 kV.

The transformer output is taken from two secondary windings, each of which supplies eight ' Com-Pak ' mercury arc rectifiers. These are arranged so that each pair of traction motors is fed in bridge by four rectifiers from each secondary. The connexions are such that the motors operate in series pairs under normal conditions, but are effectively in parallel under wheel-slip conditions. Return current to the track is taken through earth brushes running on the outer ends of the road wheel axles.

**RECTIFIERS AND TRANSFORMER.**

To meet the traction duty requirements of minimum size and stability in operation, liquid cooling is used for the excitron type rectifiers. Separate cooling circuits for the anodes and cathodes ensure that the optimum anode and cathode temperatures are maintained under thermostatic control to within close limits.

**COOLING.**

Each motor-generator blower set supplies air for two traction motors and one half of the electrical equipment. The axial type blower is mounted vertically below the motor generator, drawing air through the rectifier radiator mounted behind louvres in the body side. From the blower the air is passed downward into a duct, from which feeds are taken to the

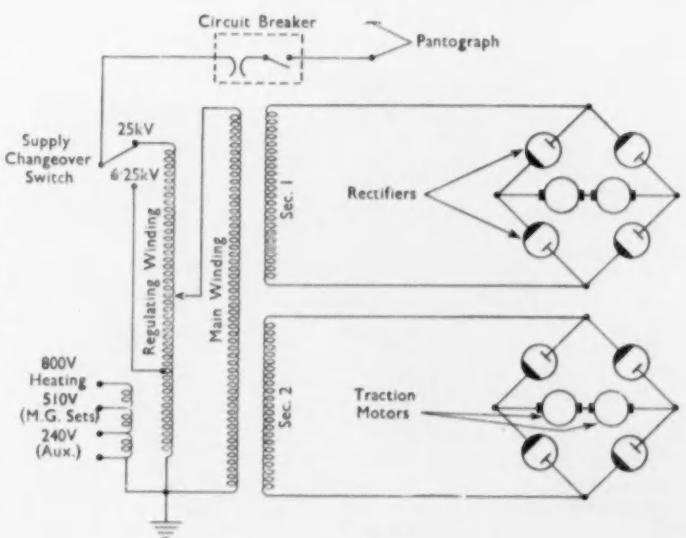



*Fig. 6.—Basic power circuit diagram.*

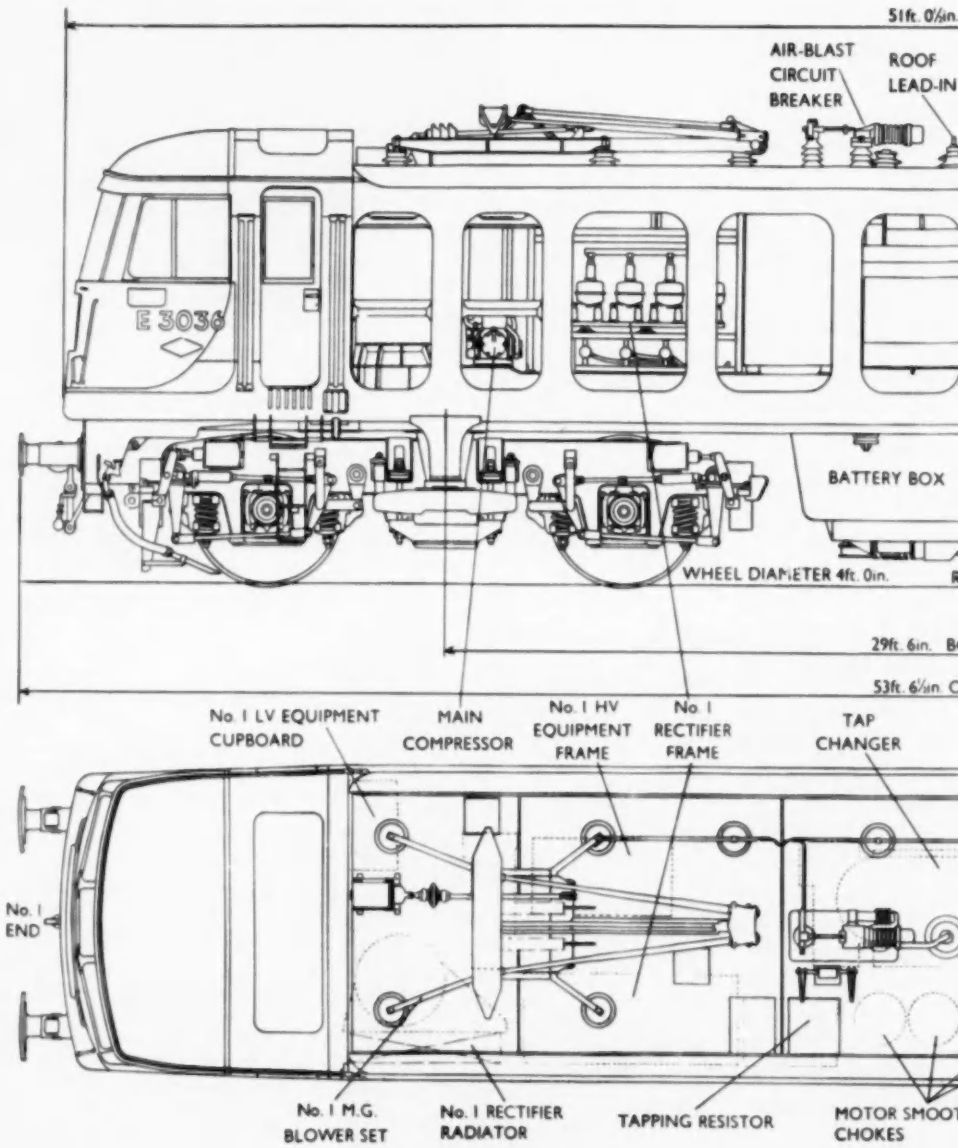
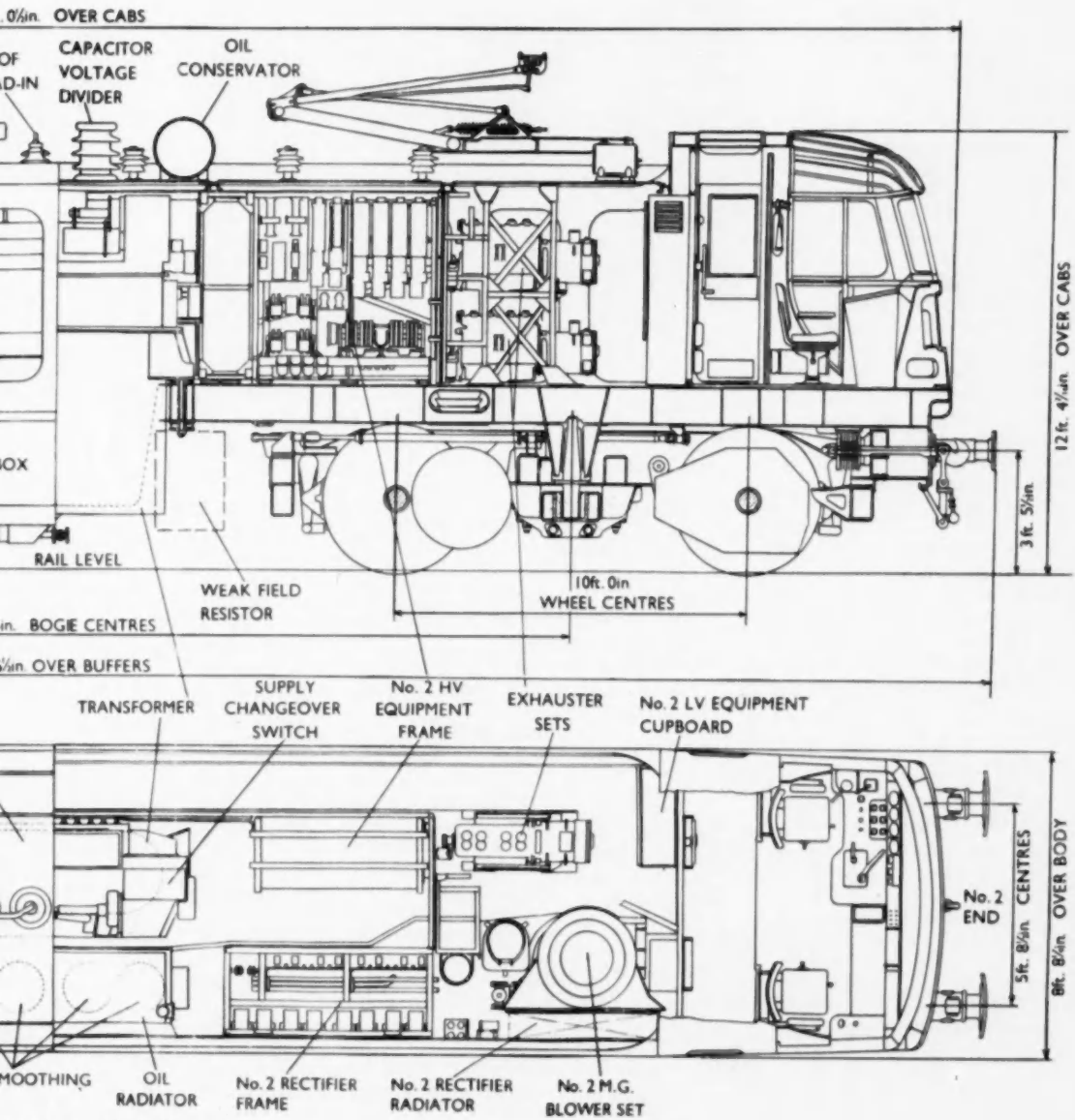



*Fig. 4.—General*




*neral layout of 25 kV locomotive.*

traction motors and to the air-cooled main motor chokes and the transformer-oil radiator. Air flows upwards through the motor chokes and through one half of the horizontally mounted oil radiator, being discharged to atmosphere through a hooded cowl on the roof. Pumps for the rectifier coolant and transformer oil circulation are driven by small induction motors supplied from an auxiliary winding on the main transformer.

**CONTROL SCHEME.**

The transformer is provided with a separate tapped regulating winding under the control of the H.V. tap-changer, arranged to give a total of 38 steps of voltage regulation. The regulating winding is connected as an auto-transformer to which the H.V. input is fed ; the 25 kV input is applied to the whole winding length and the 6·25 kV input is tapped in at approximately one quarter of the length. The voltage appearing in the main winding on the final tap is 12·5 kV for a nominal line voltage of either 25 kV or 6·25 kV.

The tap-changer has been specially developed for traction applications and combines positive step location with the ability to run through rapidly either up or down, thus facilitating quick switching operations. It comprises a series of cam-operated non-current-breaking tap selectors immersed in oil, and four cam-operated air-break diverters on which all current making and breaking is carried out. Of the 38 steps provided, 19 are transformer tappings ; the other 19 are obtained by inserting resistance in the circuit.

The master controller is arranged to give either individual notch control or automatic run-up or run-down. A total of 40 notches is provided, comprising the 38 voltage steps already mentioned, followed by two steps of motor-field-weakening on full voltage. An overcurrent relay is arranged to lift at a predetermined current to arrest further notching, so as to reduce the likelihood of tripping the overloads under run-up conditions.

Each traction motor is fed through an overload-controlled electro-pneumatic contactor and a second contactor which are used together for motor isolation. The two steps of field weakening are provided by means of divert resistors and a permanent smoothing divert resistor is connected across each field. Reversal is effected by two electro-pneumatically operated two-motor reversers.

The principal high-voltage line protection is provided by two current-transformer units, one connected in the 25 kV feed to the main transformer and the other in the 6·25 kV feed. These operate the coils of a master overload relay which trips the air-blast circuit breakers. A direct-operating overload relay is also connected in the primary of the main transformer to provide protection against faults on the secondary and rectifier circuits by tripping the circuit breaker. HRC fuses are used throughout for the protection of the auxiliary circuits up to and including the 800 volt heating circuit. The main transformer is additionally protected by a Buchholz relay, and earth-fault protection is provided on the traction motor circuits.

**MOTOR-GENERATOR BLOWER SETS.**

Each of the two vertically mounted motor-generator blower sets incorporates a single-phase a.c. driving motor, a d.c. generator and an axial-flow blower. Power for the driving motors is taken from an auxiliary winding on the main transformer, and for starting purposes the sets are run-up to speed by motoring the generator from the battery, automatic changeover to the a.c. supply being provided.

The output voltage of one set is regulated and is used to charge the battery, and also to operate one exhauster set and the auxiliary compressor. The other set, which is not voltage regulated, operates the main compressor and the second exhauster set. Provision is made in emergency for isolating either set, all essential duties being then taken over by the other.

*Fig. 7.—Traction motor and drive unit.*

**TRACTION MOTORS AND DRIVES.**

The four traction motors are six-pole series-wound force-ventilated machines provided with compensating windings. Class H insulation is used throughout and the ratings are as follows :

Continuous rating 750 h.p. 725 A 850 V 1165 rev/min.

One hour rating 890 h.p. 875 A 850 V 1100 rev/min.

The motors are mounted through rubber pads in the bogie frame, and have fabricated frames to which are bolted the hubs of the Brown Boveri spring drives which accommodate the

relative movement between motor and axle. The motors are supported in the bogie frame by two brackets on the motor frame and an arm extending from the hub of the Brown Boveri drive, forming a three-point mounting.

The drive comprises a 5° single-helical reduction gear with a ratio of 25/74, the large wheel of which is mounted on a quill shaft carried in roller bearings in the drive hub. In the face of the gear a ring of spring-loaded pads engage with face dogs integral with a spider pressed on the road wheel hub. The drive is thus torsionally flexible and the axle is free to move vertically inside the quill shaft. Oil bath lubrication is provided. The traction motor with drive unit attached is illustrated in fig. 7.

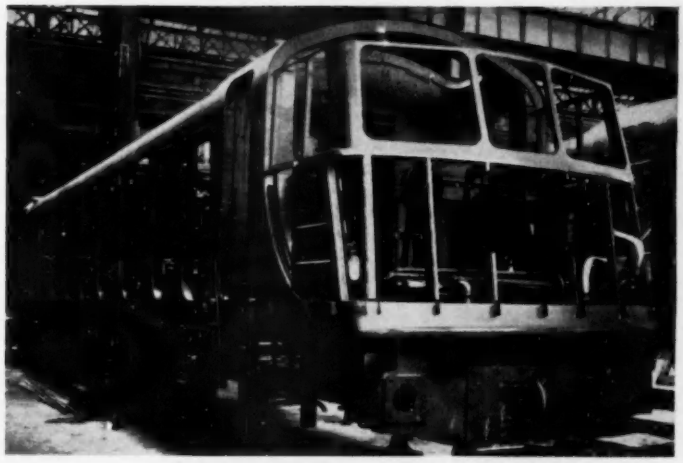


*Fig. 8.—Locomotive frame under construction.*

**DRIVERS' CABS.**

The drivers' cab at each end of the locomotive (fig. 1) follows closely the size and layout established by the British Transport Commission and approved by the Railway Unions, with minor adjustments dictated by the constructional methods adopted. Fully adjustable seats are provided for driver and assistant driver at the full-width desk, and draught screens behind each seat extend the full height of the cab.

A double-skinned roof, packed with insulation, is provided and the steel framing of the cab front and the robust construction of the desk are designed to give a measure of collision protection to the crew. Electric heaters are fitted alongside and behind each seat and in the vestibule, and the windows are glazed with 'Therglass' screens for electric de-misting. These screens are of laminated glass with a fine wire matrix, invisible to the naked eye, incorporated in the laminations.

**MAIN FRAME AND SUPERSTRUCTURE.**

The main frame base and body framing are formed entirely of thin steel plate as an integral structure (fig. 8). This design, which is the result of considerable stress analysis and investigation, eliminates all unnecessary material and weight, and provides a carefully proportioned and distributed stress throughout the complete structure. The base is a full-width shallow box section and is curved round and upwards to form the bases for a series of vertical pillars. Corresponding sections of the cant rail are curved downwards to form the top junctions of the pillars. Large radii are used to avoid stress concentration, and in effect each of the body sides forms a Vierendeel truss.

In the central portion of the width, the top deck is raised and the bottom plate lowered to increase the depth of the box section. At the pillar locations, box-form webs extend between the top and bottom decks of the main-frame base, and the two decks are also tied and reinforced by a number of longitudinal webs. The vertical members at the location of each cab rear bulkhead, and at the front door pillars, are curved over to form the roof arches. These are tied together and deep side-gussets transfer a proportion of the buffing loads evenly through the structure to the body side-frames. The drag boxes, which are fitted with standard B.R. draw hooks and screw-couplings, are arranged for the later installation of automatic central couplings, and are fitted with oval-headed hydraulic buffers. The complete frame has been designed to withstand a standing and buffing load of 200 tons without overstressing any part. Strain gauge tests carried out on one of the frames have successfully demonstrated its ability to meet these requirements.

Between the cabs, the roof is removable in five sections to allow for the lifting out of main equipment for overhaul purposes, the roof skin of aluminium alloy being attached to a light steel framework.

**BOGIES.**

The four-wheel bogies are of the swing bolster type, with welded box-frames fabricated in $\frac{3}{8}$ in. steel plate. The weight of the superstructure is transferred to the bogies through four pillars which extend from the locomotive main frame to the bogie bolsters. These pillars, two at each bogie, are located centrally between the wheels in the longitudinal plane, and outside the centre lines of the journals in the transverse plane. The pillars terminate on spherical pads sitting in spherical seatings to which manganese-steel plates are welded. The plates in turn, slide on manganese-steel plates bearing on the bolsters, the complete assembly being immersed in covered oil baths.

Traction, braking, and transverse forces are transmitted by steel king-pins, attached to cast-steel centres which in turn are welded to the main frame. Each pin sits in a rubber-bonded steel bush fitted to the bogie bolster. The thrust point is arranged below the axle level to minimize weight transfer. Traction and

braking forces are transmitted from the bogie to the bolster by rubber-bushed traction links.

The vertical load on the bolster is transferred to the bogie via two double-coil springs at each end of the bolster. The springs seat on a bracket suspended from the bogie by spring links fitted with rubber-bonded hemispherical pads. In addition to the cushioning of vibration these also assist in centralizing the bogie after negotiating a curve. Movement of the bolster springs is controlled by hydraulic dampers anchored to the spring link brackets and to the top of the bolster. Lateral sway is checked by swing links and rubber dampers.

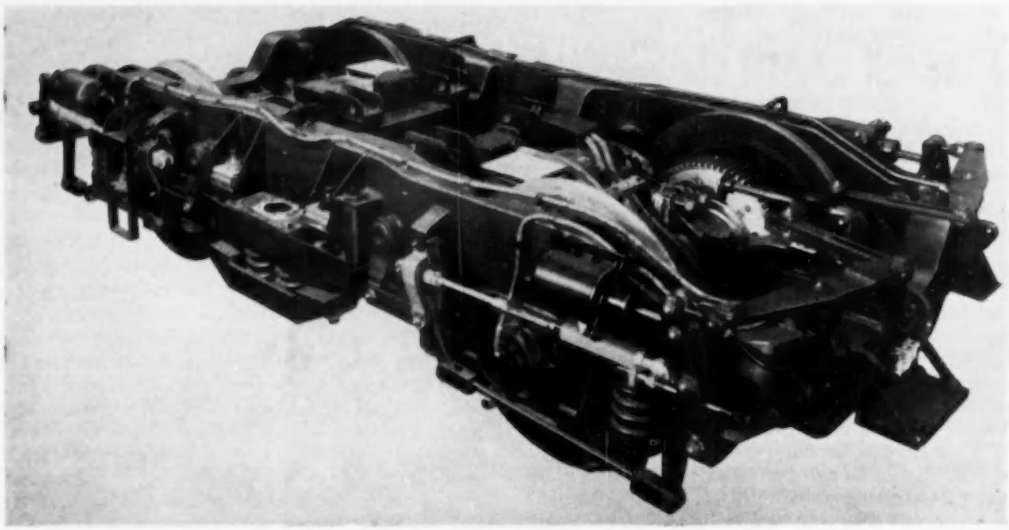


*Fig. 9.—Swing-bolster bogie showing box-frame construction.*

The bogie frame is supported on double-row roller-bearing axle boxes by two nests of coil springs at each end. The springs are rubber-cushioned at each end and attached by links to a compensating beam resting on the axle box. Manganese-steel-faced guide liners are bolted to the frame to facilitate replacement, and rolled-steel wheels and tyres are fitted.

**BRAKES.**

The brake equipment provides air braking on the locomotive and vacuum braking on the train. When hauling vacuum-braked stock, the locomotive air brakes are controlled by the driver's vacuum brake valve. The equipment is arranged for the hauling of fully braked, partially braked and unfitted stock. 8 in. diameter brake cylinders, one for each wheel, are mounted externally above the axle boxes, and operate through clasp brake rigging, automatic slack adjusters being incorporated.

Air is supplied to three main reservoirs with a total capacity of 9 ft$^3$ by a motor-driven air compressor, while vacuum for the train braking is provided by two exhausters. These run at slow speed for maintaining vacuum and are speeded up for brake release. Provision is made for the running of one exhauster off the battery for limited periods while traversing dead sections in the overhead line. The hand brake in each cab operates through the power brake rigging on one pair of wheels on the adjacent bogie.

Anti-slip braking is provided under the control of pushbuttons on the driver's desks, to give a limited brake application so as to reduce the tendency to slip under poor adhesion conditions. Sanding is provided for the leading wheels of the front bogie in each direction of travel, the sand boxes being incorporated in the cab structure, with filling doors in the cab sides. It is, however, expected that the use of sand will be unnecessary in view of the electrical characteristics of the scheme, which limit the tendency to uncontrolled wheelspin, and the provision of anti-slip brakes.

# The 1301 Data Processing System

By R. BIRD, Ph.D., M.Sc., D.I.C. and J. H. WENSLEY, B.A.
(Computer Developments Limited)

*This system has been designed jointly by the G.E.C. and International Computers and Tabulators Ltd., to provide an accurate and reliable means of processing commercial data in the decimal scale or in sterling. The high operational speed of the system also makes it suitable for many scientific and engineering calculations. In this article the authors trace the considerations affecting the basic design of the computer and describe in detail the function of the various units.*

## INTRODUCTION.

COMPUTER DEVELOPMENTS LIMITED (C.D.L.) was formed four years ago as a joint company of The General Electric Company Limited and The British Tabulating Machine Company Limited, with the object of securing for both of them a major position in the computer field. The British Tabulating Machine Company Ltd. on January 29, 1959, merged with the Powers-Samas Accounting Machines Limited to form International Computers and Tabulators Limited (I.C.T.).

The whole field of processing of numerical data has much in common, whether the calculations are carried out on a desk calculator or on a computer. In the case of the desk calculator, numbers upon which operations are to be performed are inserted by means of a set of keys and the operations which must be performed upon these numbers are put into the machine by depressing special buttons (such as 'Add', 'Subtract').

The next stage in the development of calculating devices was achieved with the various punched-card equipments, and in these the data were coded and fed to the machine by means of cards with punched holes. The 'programme', or set of instructions or operations which must be obeyed, was determined by a series of connexions which were set on

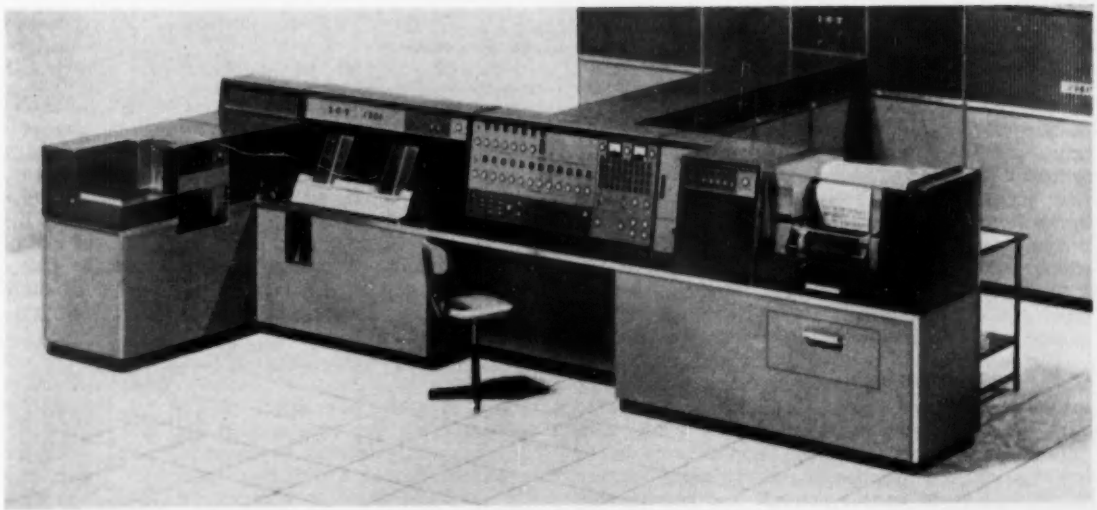


*Fig. 1a.—Basic 1301 data processing installation.*

a plug-board. This plug-board caused the numbers to be routed along certain channels within the calculator, where they were processed in particular ways : e.g., two numbers which were to be added would be routed to the input of the adder and the result would emerge from the output to be suitably stored. With the punched-card calculator, which is more automatic than the desk calculator, it is not possible for intermediate results to be noted on paper by human intervention. It is, therefore, necessary to provide the machine with facilities for storing these results, and this may be carried out in a variety of ways, such as magnetic drums. The main limitations of a punched-card calculator are in the finite size of the plug-board, which limits the complexity of the calculation which can be carried out, and the inflexibility of this plug-board, which makes it difficult to modify a programme. In fact, this modification is normally carried out by the removal of one plug-board and the insertion of another, suitably wired to carry out the modified programme.

The computer differs from a calculator in that the facilities for storage are greatly increased, and also the instructions are stored in a coded form along with the data, instead of being wired into a plug-board. This permits much more complex programmes to be inserted into the machine and hence more complex calculations to be carried out. It also permits easy modification of a programme and this can be carried out automatically by another part of the programme. By this means very varied calculations can be performed during one run of the data through the machine.

Data processing would be carried out in a computer in the following way. Firstly, the programme of instructions would be fed into the machine via some input device such as a punched-card reader. These instructions would be stored within the computer, and when this is completed the first set of data would also be fed to the machine (once again through the punched-card reader). The data would now be passed into what is termed an arithmetic unit, where all necessary calculations would be carried out. During this calculation intermediate results would be held within the store and called upon when necessary. At the end of the calculation all results would need to be transferred out of the computer, and this may be done in a variety of forms, examples of which would be printing or punched cards.

In the preceding paragraph, input data were not distinguished as to types. In most commercial and in some scientific calculations part of the information which is fed into the computer has been carried forward from the last run of this programme. Using the particular input and output mentioned above, this would be achieved by punching out carried-forward information on the cards, which before the next run

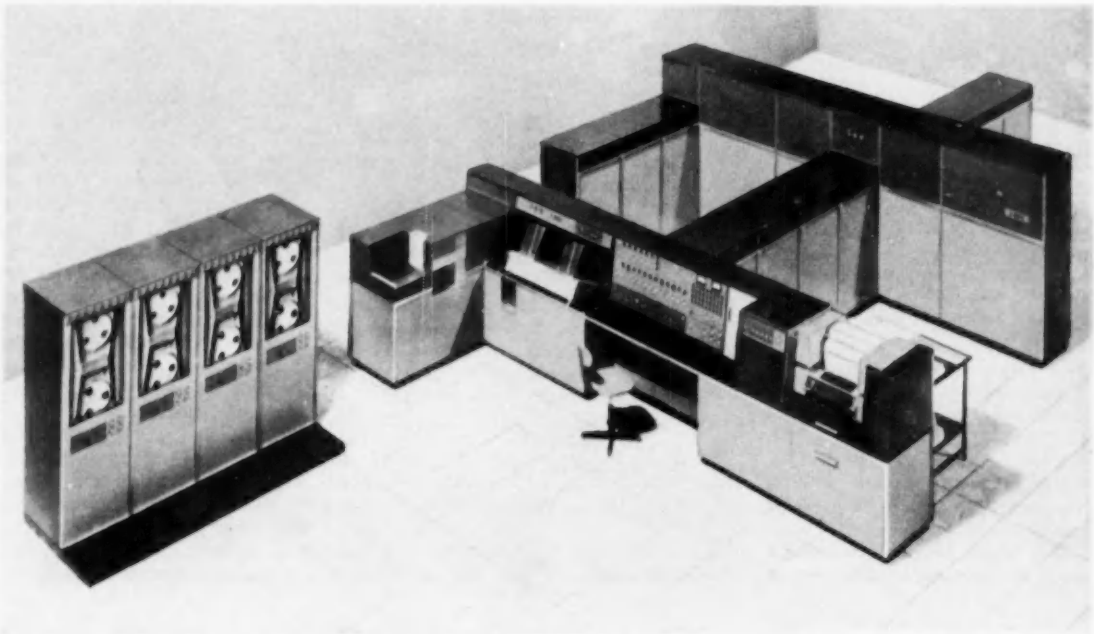


*Fig. 1b.—1301 data processing installation with four additional magnetic tape transports (left), and increased magnetic drum storage.*

of this programme would be merged with cards containing new data and the combined set would be used as the new input.

In view of this fact, when considerable quantities of data must be transferred out only to be reinserted into the computer, there is a need for a device which will carry out this operation in an economical way and at a high speed. This requirement is met by the use of magnetic tape, which can be recorded during one run and the reel removed from the ' tape-transport ' and reinserted for the next run of the programme. This reinsertion would take place at the same time as any raw data were being inserted via the punched-card reader. This mode of operation is particularly applicable where the calculation is one of updating a file, such as a stores record.

In a digital computer, numbers are usually represented in a coded form by means of electrical impulses. The presence or absence of a pulse would represent the presence or absence of a digit of a particular weight, the actual weight being dependent upon the position of this electrical pulse, frequently its position in time. A particular form of coding used is known as binary coded decimal, in which each decimal digit is represented by a combination of pulses in each of four positions, the weight of the four positions being 1, 2, 4 and 8; e.g., if there is a pulse in positions corresponding to 2 and 4, but not in positions corresponding to 1 and 8, then the digit represented would be 6. This particular representation of a decimal digit would be repeated for as many digits as are required to specify a number. In computers, allowance is frequently made for the maximum number which it is necessary to represent, and this will be of the order of 10 or 12 decimal digits. Other representations, such as the pure binary scale of numbers, are often used.

Thus the identifiable functional units within a computer are : Arithmetic Unit—Input Equipment (e.g., punched-card reader)—Output Equipment (e.g., printers, card punches)—Storage—Magnetic Tape System—Control. The control unit is the means by which the stored instructions are correctly interpreted and the correct sequence of operations carried out. This is achieved by a suitable de-coding of the instruction and the setting of electronic switches which route numbers to the appropriate units, and at the appropriate times, for the correct operations to be carried out. In certain cases certain sub-controls are necessary within the computer, and these are frequently associated with input/output equipments or the magnetic tape system.

The concept of the 1301 data processing system, fig. 1, was originated by C.D.L. and evolved by them in conjunction with its parents. The design was aimed at, and has achieved, a high ratio of productivity to cost. I.C.T. have provided the commercial knowledge and experience, the punched card input/output equipment, the magnetic drum store, and the magnetic tape transports, while G.E.C. has been responsible for the subsequent development of all the electronic circuits and the appearance design. The system, production prototypes of which are now under test at G.E.C. Telephone Works, Coventry, has been specifically designed for commercial data processing, but its high speed makes it equally suitable for many scientific and engineering calculations. The input to the data processing system centre, that is the electronic computer, is by means of punched cards and the output of information is in the form of punched cards or documents produced by a line printer. The basic medium-size computer is fitted with a high-speed magnetic core store and a large-capacity magnetic drum. The high inherent productivity of the computer enables it also to be used as a large scale system when fitted with additional core store, magnetic drums and magnetic tape storage. The electronic circuits of the machine are completely transistorized.

**SUMMARY SPECIFICATION.**

**INPUT.**

80 column punched cards read and checked at 600 cards/minute.

**PRINT OUTPUT.**

120 print positions per line with 50 possible characters per position.
570 full lines/minute average when continuously printing.

**PUNCH OUTPUT.**

80 column punched cards punched and checked at 100 cards/minute.

**STORAGE.**

Core Storage : 400 (4800 decimal digits) word blocks in multiples up to 2000 words.
Magnetic Drum : 12 000 words/drum. 5240 revolutions/minute.
Up to 8 drums per machine.

**ARITHMETIC UNIT.**

1 Megacycle/second pulse repetition frequency, serio-parallel mode of data transfer.
Decimal or sterling (binary coded).
Word—12 decimal or sterling digits.
2 (short) instructions per word.

**MAGNETIC TAPE.**

Two alternative systems.
(*a*) 90 Kilocycles/second numeric digit rate on 1 in. tape.
(*b*) 22·5 Kilocycles/second numeric digit rate on ½ in. tape.
Reading and recording on separate tape transports simultaneously.
Single binary digit (bit) error correction ; double bit error detection per character.
Up to 8 transports per machine.

**OTHER FEATURES.**

Comprehensive display console.
Marginal checking for servicing.
Transfers to and from stores are checked.
' Transistorized ' throughout.
Wrapped connexions, modular construction and printed wiring.

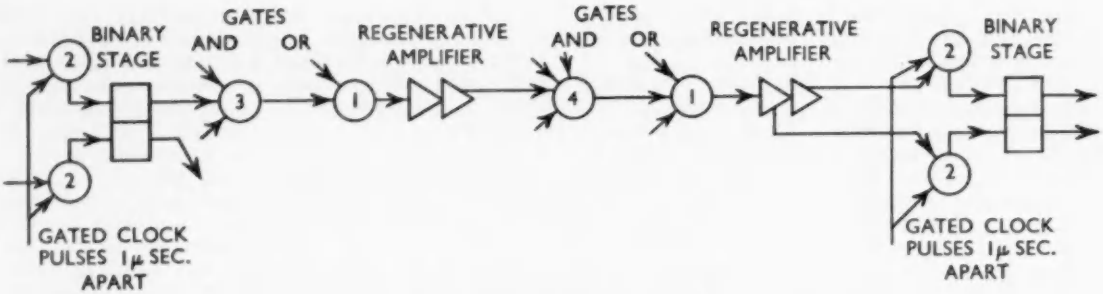



*Fig. 2.—Typical sequence of logic circuits.*

**CIRCUIT ASPECTS.**

At the commencement of the design of this machine, evidence from G.E.C. Research Laboratories and elsewhere showed that transistors were about to reach a state of development when they were not only considerably more reliable than thermionic valves, but more economical and capable of operating at the necessary speeds. Transistors were, therefore, chosen exclusively for the active elements in the basic machine, and the consequent reductions in size and heat are added advantages of this step.

The high-speed computing circuits in the 1301 computer use Eccles-Jordan type binary circuits, and germanium-diode and transistor gating circuits in logical operations. The circuits are asynchronous and are therefore used at any frequency up to the arithmetic-unit operating frequency of 1 Megacycle/second and during the one microsecond period between successive clock pulses two AND-OR gating operations may be performed. A typical logical chain sequence is shown in fig. 2.

The frequency at which the machine operates is controlled by a ' clock track ' on the magnetic drum, which produces a frequency of nominally 250 kilocycles/second. This frequency is multiplied by 4 to produce the main machine clock.

**STORAGE.**

In order to match the fast arithmetic unit necessary for computation and input/output control, a small high-speed ferrite torroidal core store of a minimum of 4800 decimal digits, equivalent to 400 words, has been provided.

Any word may be selected in 3 microseconds, and a new word substituted for it in a further 4 microseconds. Each word consists of 50 binary digits ; 48 of these are coded in 12 groups of 4 binary digits, each group representing one of 12 sterling or decimal digits. The other 2 binary digits are checking or parity digits which confirm the accuracy of data transferred both in and out of the store.

The 48 bits of each word of the core store are checked in 2 halves ; one half with an odd parity digit and the other half with an even parity digit. In these circumstances all single-bit errors in a word and some multiple errors will be detected. Also, machine faults which might cause the data to become all ' 0's ' or all ' 1's ' will be detected.

For those users who need more than 400 words of immediate quick-access storage, it may be increased, in increments of 400 words, up to 2000 words maximum. Since the computer will require more than 400 words of storage for a complete programme, it is ' backed up' by a larger, slower-access time store on a magnetic drum (fig. 3) containing 12 000 words.

The drum surface is divided into 240 circumferential tracks grouped in fours to form 60 bands, each band containing 200 words. Since the drum revolves at approximately 5240 revolutions per minute, a band of

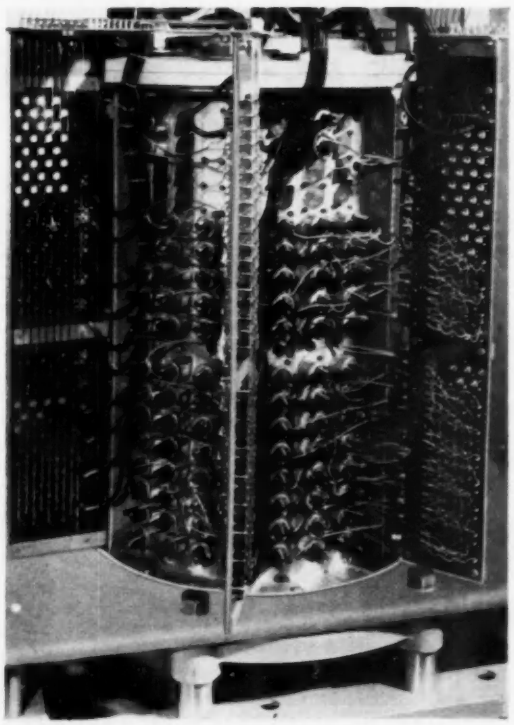


*Fig. 3.—Magnetic drum store.*

information may be transferred to or from the core store within 11 milliseconds. The computer has been so designed that the transfer may start at any of 20 points during a revolution, so reducing the access time (that is, the waiting time before transfer can commence) to under 1 millisecond. As practical programmes involve a number of such transfers this feature increases the overall speed by reducing the access time. The computer may be fitted with up to 8 drums.

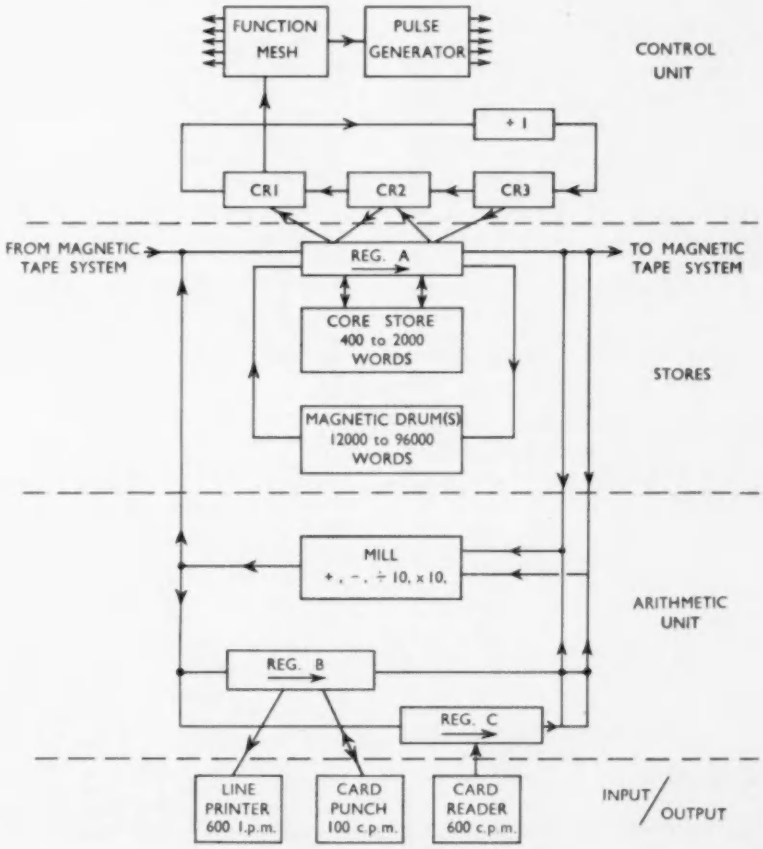



*Fig. 4.—Logical structure of basic computer.*

On each track of the magnetic drum, information is recorded at approximately 130 binary digits per inch. The magnetic drum information is checked by the addition of 4 bits to each word. The 4 bits for each decimal digit are recorded simultaneously on 4 adjacent drum tracks and the 4 check bits are similarly recorded at the end of each word.

**ARITHMETIC UNIT.**

The choice of word length depends not only on the maximum length of numbers normally met with in business and mathematical computations, but also on the number of digits in the computer instructions. A 12 decimal (or sterling) digit word was chosen since 12 digits are adequate but not excessive for commercial data, and also they allow the storage of two 6 digit instructions in one word.

The choice of scales in which a computer functions for commercial calculations lies generally between those of binary and decimal with or without the possibility of calculating directly in sterling. The binary scale was rejected due to the time and storage capacity necessary for conversion of decimal and sterling quantities to and from the binary scale. The choice, therefore, was decimal with or without the ability to work directly in sterling. The conversion time from £ s. d. to decimal for every sterling quantity unnecessarily reduces the productivity in a commercial computer, and therefore at small extra cost the machine has been designed to calculate directly either in the decimal scale or in sterling.

The cost of an arithmetic unit (fig. 4) is generally determined by the number of registers which have to be employed to carry out the arithmetic. In the case of the 1301 the core store register (register A) can also be used for temporary storage during arithmetic processes, and it is found that with the addition of two other registers (B and C) a suitable arithmetic unit may be designed.

Simple operations such as addition and subtraction are carried out utilizing registers A and B, the answer may be left in register B or may be returned to the core store. Register C is employed only during multiplication and card reading. The multiplication technique is effectively one of successive addition or subtraction and is capable of carrying out multiplication of a decimal multiplier with a decimal or sterling multiplicand. The number of registers is kept to a minimum in this computer by retaining only 12 digits of the product of two numbers. The particular 12 digits which are retained are controlled by a number stored in a separate single-decimal digit store termed the decimal point register.

The 1301 computer carries out all basic arithmetic processes in a single unit termed the mill, which is capable of adding or subtracting decimal or sterling numbers and multiplying or dividing sterling numbers by 10. It is found that by incorporating all these functions into one unit, considerable reduction of equipment is achieved over the alternative of providing separate units for each separate function. Some basic operation times of the arithmetic unit are as follows (time for extraction of the order from the core store is not included) :

| *Function* | *Time in microseconds* |
|---|---|
| Add | 21 |
| Subtract | 21 |
| Store | 21 |
| Left shift | 34 |
| Right shift | 17 |
| Multiplication | 160 approx. for each decimal digit in multiplier |
| Input/Output control | 12 |

The arithmetic unit is provided with indicators at the output of the mill which sense the state of the result emerging from the mill. These indicators may be tested by programme and sense the conditions : positive, negative, zero and overflow.

## CONTROL UNIT.

The control unit of a computer determines in detail the actions to be carried out by all units at all times. In certain cases there are small subsidiary controls for certain specialized units and in the 1301 computer, the drum control is an example. The magnetic tape system, described below, also has its own control system. Basically the control of a computer requires the stipulation of *what* must be done, *where* it must be done, and *when* it must be done. These three functions are mainly determined by the control register, the function mesh and the pulse generator respectively. In the majority of operations the operative part of the control register is that marked *CR*1 in fig. 4. This part-register is 6 digits long and for most orders the two most significant digits represent the function which must be obeyed and the four least significant digits represent the relevant address in the core store. The two function digits are fed from *CR*1 to the function mesh where a recoding takes place and outputs are fed from the function mesh throughout the machine, opening the appropriate gates for the appropriate actions to be carried out. At the same time, outputs from the function mesh stimulate the pulse generator so that the correct sequence of pulses is produced which will control the movement of information within the computer in the required sequence. In the case of complex operations, such as multiplication, many smaller operations (micro-orders) must be carried out within one order. Further inputs to the function mesh are provided (not shown on fig. 4) which form a special control for multiplication and also control the output of the function mesh, and thence the outputs of the pulse generator.

As mentioned, most operations in the 1301 are controlled by the digits of control register *CR*1. However, certain operations require more digits to specify them than can be stored within *CR*1 and in this case *CR*2 is also used. An example is a drum transfer order which causes information to be transferred between the magnetic drum and the core store.

Core store words containing orders are transferred from the core store to *CR*1 and *CR*2 via Register A in such a manner that *CR*1 is loaded with the six most significant digits of the word in the core store. Assuming that this is a single length order (i.e., six digits), the operation is performed and at completion, the information in *CR*2 is transferred to *CR*1.

In the 1301, when a new pair of orders is transferred to the control register, the contents of *CR*2 and *CR*3, the previous order, are transferred to Register A from whence they can be transferred into the core store. This is a particularly useful feature in that it implies that if a transfer of control is given by the programmer, into a sub-routine for example, it will be possible by examining Register A after the transfer of control to determine from what part of the programme the transfer took place. This facility is utilized in constructing a link to and from sub-routines.

## INPUT/OUTPUT.

In the 1301 computer the high pulse-repetition frequency of 1 million per second used in the electronic circuits enables the computer not only to compute very rapidly, but also to operate its input and output equipment without additional expensive control circuitry and buffer stores.

The input/output equipments themselves consist of a card reader, a line printer and a card punch. The card reader feeds 80 column punched cards endwise at a rate of 600 cards per minute. The card holes are sensed by 12 photo-electric cells, one per card row :

a separate set of 12 photo cells reads the card again, for checking purposes ; the computer compares the two readings by programme. If a card has been erroneously read, or for any other reason it is required to separate it from the rest, it can be diverted from the normal card stacker into a special reject stacker. The contents of the normal hopper and stacker are 2000 cards each. Information is fed to the 1301 from the card reader via register C (fig. 4).

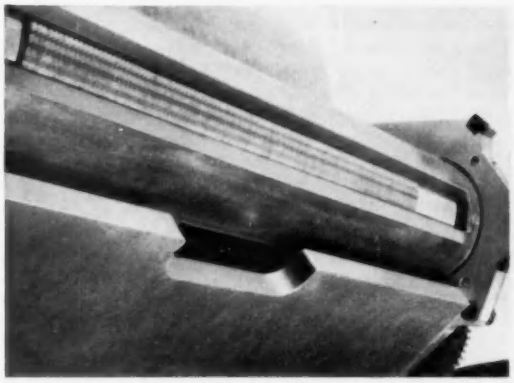


*Fig. 5.—The print barrel.*

The line printer, operating on the ' hit on the fly ' principle, which can print up to 4 copies, produces a line of up to 120 characters. The 120 print wheels, which have 50 characters each round the circumference (fig. 5), revolve continuously at 800 rev/min, and the 120 print hammers force the paper on to the type face very rapidly at the required time while the wheels are in motion. Fig. 6 shows the principle of operation. The sharp hammer blow is obtained by passing a short current pulse, of approximately 500 microseconds duration, through the print-hammer magnet coil, causing the hammer to accelerate rapidly. The hammer shaft prints the character, and springs away rapidly, avoiding smudging. With this high printing rate the overall speed of document production depends equally on the rate of line spacing and, for longer gaps, the rate of ' paper throw '. Continuous speeds of up to 570 lines per minute of 120 characters each are obtainable in practice. As on the card reader, equipment is saved by using the computer to the maximum. During the revolution of the type wheels the programme decides, as each character passes, whether the hammer needs to be operated.

The card punch operates at 100 cards per minute. The information to be punched is routed by programme to the magnets controlling the 80 punch knives 12 times per card cycle, once for each row on the card. The whole of the information punched on the card is read back into the computer during the next card cycle, and compared with the information it was desired to punch, thus verifying its accuracy.

**MAGNETIC TAPE.**

The computer has been designed for the fitment of magnetic tape either initially or after installation in the customer's office. Magnetic tape may show advantages over punched cards, justifying its extra cost, on various tasks, particularly those requiring the maintenance of large files of information. The high-productivity tape system has a data rate of 90 000 numerical characters per second. This is obtained by using 1 in. wide magnetic tape with transports operating at 150 in. per second. Up to eight separate tape transports may be fitted to one computer and information may be read from one transport at the same time as recording the same or different information on another. Characters are spaced at 300 to the inch on the tape. Each character is examined for errors and if one binary digit used in the character code is wrong it is not only detected, but corrected. If there are two erroneous binary digits in a character (a very unlikely event) they will be detected and the computer, if recording, will record the information again, and if reading, will attempt to read it again. Since all information is checked after recording, and error correction is used on reading, the security is extremely high. A second

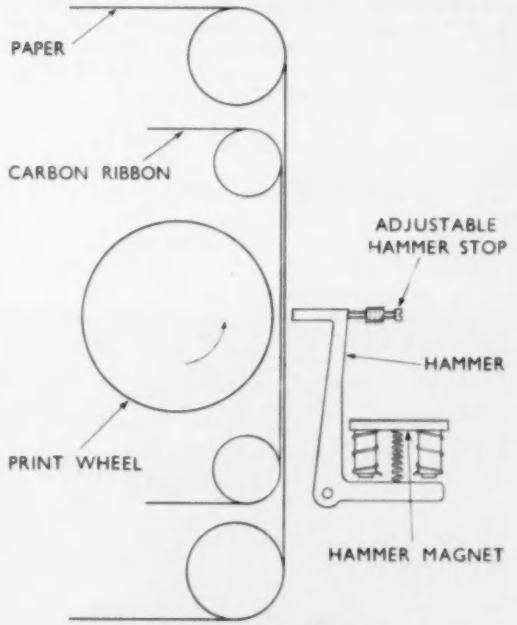



*Fig. 6.—The print mechanism.*

tape system of lower productivity but at a reduced price, having a data rate of 22 500 characters per second, is also available for those applications where its speed is adequate.

Economy of equipment is achieved by utilizing only one reading and one writing unit for the tape system. Multi-pole electronic switches are provided, which can be controlled by programme, and which enable the

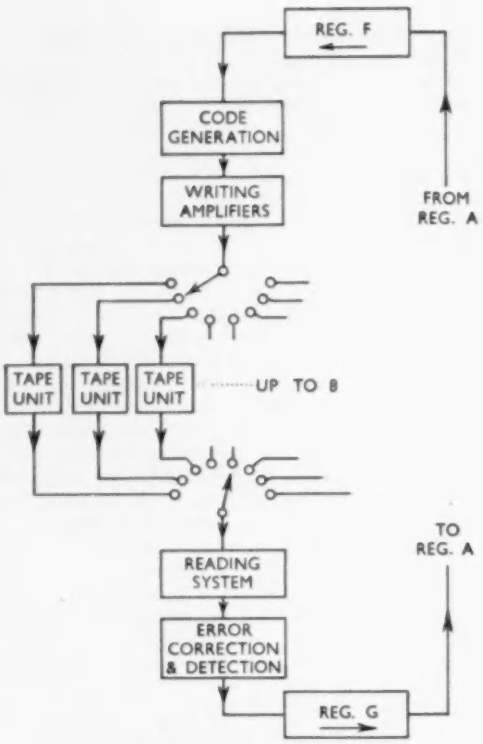



*Fig. 7.—Magnetic tape system.*

reading and writing units to be connected to any of the tape units up to a maximum of eight (fig. 7).

The central computer and the magnetic tape system are connected by a ' data transfer unit ', which controls the time sharing of the core store between tape system and arithmetic unit. It is possible to carry out calculations simultaneously with reading and writing on magnetic tape. During this simultaneous operation the tape system signals to the data transfer unit when it requires a new word from the store (i.e., during writing on tape) or when it requires to place a new word into the store (i.e., during reading tape). The data transfer unit, upon receipt of this signal, halts the arithmetic operations of the computer for 16 microseconds, while the necessary transfer takes place between core store and tape systems ; it then causes the arithmetic operations to be continued. This ' break in ' takes place approximately every 133 microseconds for reading or writing using the high-productivity tape system. It is not necessary to take into account this break-in when writing the ' arithmetic ' programme, as all action is automatic and only results in a slight slowing down of the speed of processing of the arithmetic calculation.

## PHYSICAL CONSTRUCTION.

Considerable attention has been paid to the design and the physical construction of the electronic units and their integration with the input/output units and magnetic drum. Many conflicting factors have been reconciled and the high-frequency signals (with waveform-rise times of the order of 100 milli-microseconds) are conveyed on open air-spaced wiring within the machine. No plugs and sockets are employed, since they are an inherent source of unreliability, and all connexions are soldered or ' wrapped '. The wrapped connexions, fig. 8, are formed by clamping together two rectangular cross-sectioned tags by means of a tightly-wound helix of tinned copper wire. This forms a very reliable joint since the binding copper makes many intimate metallic contacts with the corners of the tags. Fig. 9 shows a rack of the electronic equipment with the printed circuit boards containing the electronic components mounted in rows and joined to the frame wiring by rows of wrapped joints.

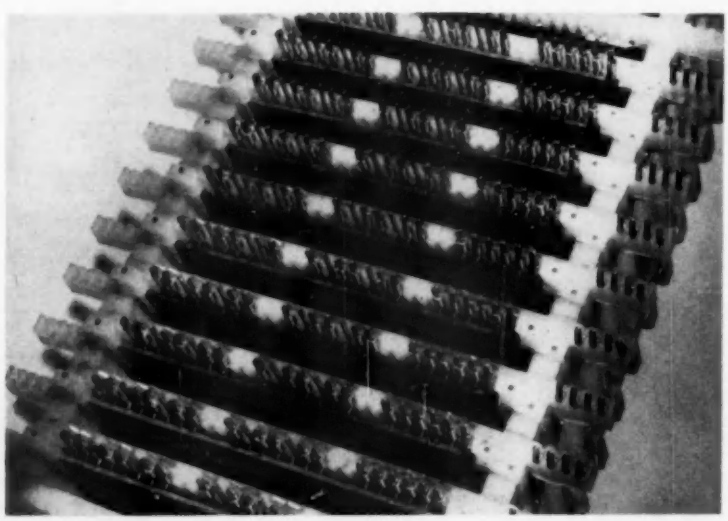


*Fig. 8.—Assembly of printed boards showing wrapped joints.*

The display console enables the operator to examine the contents of any register and also to insert manually numbers and instructions. A comprehensive display for the service engineer aids him in locating faults quickly. Extensive marginal checking facilities are provided so that incipient faults can be

eliminated during the routine maintenance periods.

**PROGRAMMING.**

As mentioned in the previous section, the detailed control of the input/output units (card reader, card punch and line printer) is carried out by the computer itself. When all 3 units are operating simultaneously it is necessary for the computer to be able to process the information coming in from the card reader and going out to the punch and printer, in such a manner that no unit has to wait beyond the allowable time. This detailed control programme is a sub-routine which is constructed once and for all and which has been designed according to certain rules governed by the time tolerance of the particular units. The complexity of this programme is such that once constructed, it would not be altered or modified by a particular user. This, however, will be no drawback to the user, who will in all cases use the standard programme and need not know the internal processes by which control is achieved on the feed, print and punch.

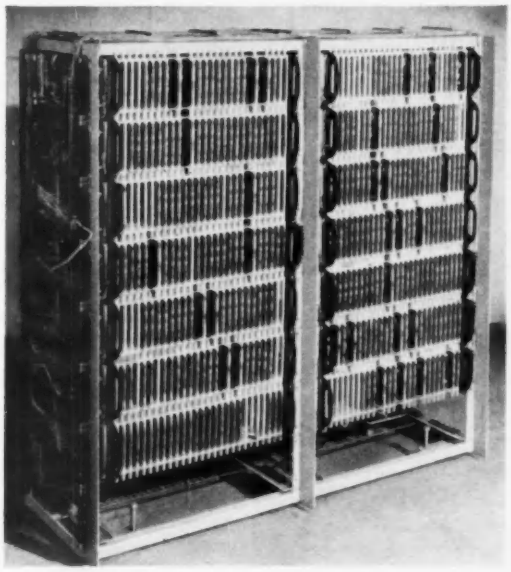


*Fig. 9.—Subsection of electronic unit.*

Orders for the 1301 computer, together with other information required for editing purposes, are punched on programme input cards. These punched cards are read and processed by a special programme termed 'initial orders'. This programme is permanently stored on a reserved band of the drum and called into action whenever a programme is to be read. It will then cause cards to be read, carry out certain housekeeping operations, such as the incorporation of absolute addresses for relative addresses, and place the orders in the correct place on the magnetic drum. On commencing to run a programme the initial orders will automatically bring down from the drum the first block of programme and direct control to the appropriate starting point of this block. The reserved band of the drum on which the initial orders are stored can only be altered by the programmer when a special switch is operated. This protects the initial orders from being overwritten inadvertently by the programmer. There is another reserved band on the magnetic drum and this will be used for storing a general programme which is capable of controlling the feed, print and punch units.

A set of sub-routines can be incorporated in programmes to reduce the number of instructions which have to be written for particular programmes.

Programming developments for the computer include a comprehensive automatic coding system, and although it is inappropriate to describe this system in any detail in this article, it is necessary to point out that a programme (termed a 'Compiler') will be available with the machine, which will convert statements describing a business procedure into machine code, producing thereby a programme which can be run at full efficiency thereafter. Considerable reduction of the time and effort necessary to produce detailed programmes for the computer will result from the use of the automatic coding system.

# Winding Plant at Littleton Colliery

By J. ARROWSMITH, Chief Engineer, No. 2 Area, West Midlands Division, National Coal Board, and W. A. UNDERHILL, Engineering Group, Erith.

*During 1959 two new electric winders were installed at the Littleton Colliery of the National Coal Board to replace the steam winders at Nos. 2 and 3 shafts. Both equipments embody the latest developments in a.c. closed-loop control practice, and one is of exceptional interest in that the installation and commissioning were carried out during the miners' annual holiday fortnight, thus avoiding any loss of output. This achievement was due to effective co-operation between the staffs of the National Coal Board and the G.E.C. and other contractors responsible for the installation of the new winder.*

As part of the modernization programme being carried out at Littleton Colliery, Cannock, Staffs, the National Coal Board placed orders with the G.E.C. for the supply and installation of two electrically driven winding engines to replace the steam winders at Nos. 2 and 3 shafts.

The new electric winder for the No. 3 shaft had to occupy the same site as the original steam winder, and, as the output of the pit had to be maintained, the contract was accepted on the understanding that the new winder for this shaft would be erected and commissioned during the miners' annual fortnight holiday period.

The floor area available in the existing winder house was found to be insufficient to accommodate all the switchgear and other equipment necessary for the electric winder. Part of the foundation blocks supporting the old steam-winder cylinders had, therefore, to be removed. At the same time, as much preparatory work as possible had to be carried out without interfering with the satisfactory operation of the steam winder, since the period available for the actual changeover was limited. Approximately four months before the changeover was due to commence, the National Coal Board therefore started preparing the foundations for the electric winder. Cavities were cut into the foundation blocks supporting the steam cylinders and rolled-steel joists were positioned beneath the cylinders to act as temporary supports ; this enabled part of the old foundations to be demolished. After the steam-cylinder supporting blocks had been removed, the foundations for the new equipment in the basement area were prepared. A new floor for the winder house was also constructed, enabling the H.V. and L.V. switchgear cubicles to be positioned and the majority of the interconnecting cables to be installed.

To accommodate the electric winder it was necessary to build on one side wall of the winder house an annexe with suitable foundations to house the main driving motor, the end wall of the annexe being left incomplete to facilitate positioning of the motor. This aperture was subsequently closed by the provision of a roller-shutter door. As the main entry into the winder house was above ground level, it was also necessary to construct a concrete ramp to facilitate the entry of all equipment. The mechanical parts of the winding engine sent to site shortly before commencement of erection were suitably marked and stored on ground adjoining the engine house in the order of erection.

The existing 20-ton hand-operated overhead crane in the winder house was motorized by incorporating an air motor into the drive. In addition, large and medium capacity mobile cranes were provided by the National Coal Board, and these were found to be extremely useful for transporting material from the stocking area into the winder house. The medium crane was also utilized for lifts in the winder house, when the overhead crane was otherwise engaged.

The installation of the Littleton No. 3 Winder took place during the miners' annual holiday, which was from Friday, July 24, until Monday, August 10, 1959. In view of the fact that this was one of the first occasions in which a double-drum clutched winder had been installed during a holiday period, a detailed programme was compiled, outlining the erection shift by shift. It was estimated that the complete programme would require 32 shifts of 12 hours duration.

The pit closed down at 4 p.m. on Friday, July 24, and demolition of the old steam winder commenced at once, the work, together with the preparation of the new foundations, being completed by 3 a.m. on Tuesday, July 28. Erection of the mechanical equipment was started immediately afterwards.

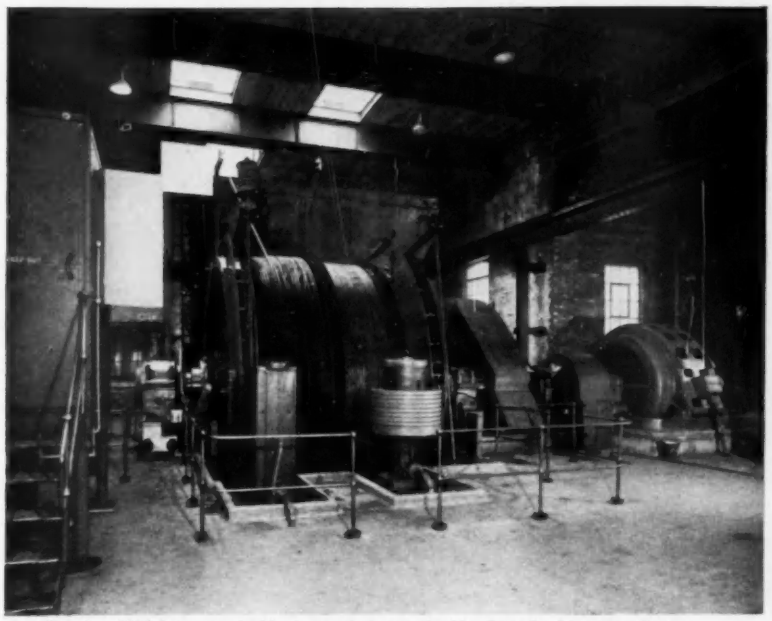


*Fig. 1.—2000 h.p. a.c. double-drum winder at the No. 3 shaft of Littleton Colliery.*

Due largely to the preparatory work and forethought by the National Coal Board and to the manner in which the confidence of all personnel employed on the changeover had been gained, completion of the erection of the electrical and mechanical equipment, which had been scheduled to be ready for light-load running by Friday, August 7, 1959 was anticipated by 48 hours.

After all tests on the motor had been carried out, ropes and cages were installed on Thursday, August 6, and the winder was finally commissioned ready for coal winding by Saturday, August 8.

## MECHANICAL EQUIPMENT FOR THE No. 3 SHAFT WINDER.

The winder (fig. 1) is of the double-drum type, enabling hoisting to be carried out from different levels as required. The theoretical duty cycle diagram for coal and stone is shown in fig. 2. The equipment is designed for an output of 220 tons of coal per hour, when winding from the maximum depth of 1634 ft.

Each drum is 16 ft in diameter at the rope centres, and 3 ft 8 in. wide between flanges. To suit the rope-angling conditions, the winder is not fitted with a centre bearing between the drums and this feature tended to simplify the erection procedure. One drum is fixed to the shaft, the other being driven through a multiple-tooth clutch. The clutch teeth are generated over the full circumference of the driven member, and give a maximum rope adjustment of 6 in. The clutch is operated by a hydraulic cylinder mounted on the outer soleplate, the cylinder being controlled by a lever on the driver's desk. Hydraulic interlocks are provided to ensure that the brake is fully applied to the loose drum before the clutch is withdrawn and conversely mechanical interlocks are provided to ensure that the brake cannot be released until the clutch is in the fully engaged position.

The drums are arranged for double-layer coiling of the winder ropes at the maximum depth, and spare rope for re-capping is carried on the drum barrel as additional dead coils. The drums are provided with machined rope-grooves and rope-risers at the points where the ropes rise from the first to the second layer. The positioning of the risers was decided after the ropes had been installed and tensioned.

The drums are driven by a 2000 h.p. a.c. induction motor through single-reduction splash-lubricated double-helical gears with a ratio of 9·94 : 1. The gear wheel is of fabricated construction, and has hobbed, gapped, continuous-type teeth. The pinion is forged integral with its shaft from high-carbon steel, and the drive is transmitted from the motor to the pinion through a flexible spring coupling. The bearings supporting both the main drum shaft and the pinion shaft have self-aligning cast-steel bushes lined

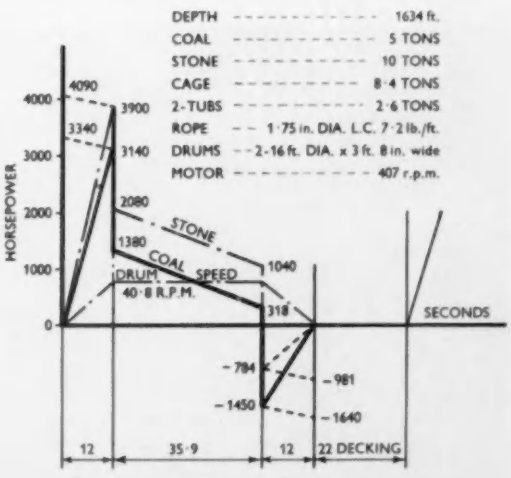



*Fig. 2.—Duty cycle for No. 3 shaft winder.*

with white metal, and are fitted with twin oil rings. Seals are provided to exclude dust and other foreign matter.

The auxiliary equipment includes a vertical twin-screw depth indicator incorporating, at the base, power-lever returning cams for the end of the wind. A loose-dial duplex Lilly Controller type 'C' gives full protection against overwind and overspeed at any point during the wind. If either of these contingencies arises the controller causes an interruption of the safety circuit. This de-energizes the emergency brake solenoid and the mechanical brakes are applied within about 0·2 second. The mechanical brakes are of the centre-suspended parallel-motion type, and have shoes machined on their faces to receive the woven asbestos friction lining. Manual and emergency application is effected by the well-proved low-pressure oil-operated brake engine, the control of which was described in detail in a recent issue of this Journal.* The control unit of the brake engine is illustrated in fig. 3.

*Fig. 4.—1000 h.p. a.c. double-drum winder at the No. 2 shaft.*

### MECHANICAL EQUIPMENT FOR No. 2 SHAFT WINDER.

The winding engine for No. 2 shaft (fig. 4) is also of the double-drum type and is capable of an output of 220 tons of coal per hour from the winding depth of 1026 ft. The duty cycle for this winder is shown in fig. 5.

Each drum is 16 ft in diameter at the rope centres and 3 ft 3 in. wide between flanges, one drum being fixed and the other clutched. The drums are driven by a 1000 h.p. a.c. induction motor through double-reduction splash-lubricated gears with a ratio of 22·26 : 1. The first reduction comprises a carbon-steel pinion and a fabricated steel wheel with double-helical continuous-type teeth. The second reduction comprises a forged carbon-steel pinion and a fabricated steel wheel with straight involute teeth. In other respects the mechanical details of the No. 2 shaft winder are identical with those of the No. 3 equipment.

The No. 2 winder was erected in a new house positioned at the rear of an existing winder house, which contained an old steam winder. The changeover from steam to electric winding took place during a prearranged weekend, after which the old steam winder house was demolished.

* *G.E.C. Journal*, Vol. 26, No. 3, p. 121, Summer, 1959.

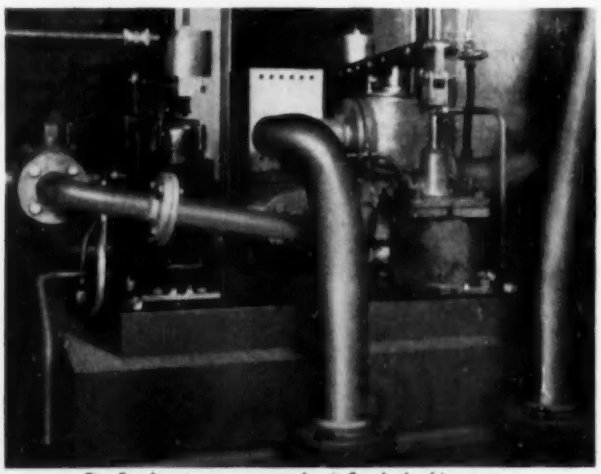


*Fig. 3.—Low pressure control unit for the braking system.*

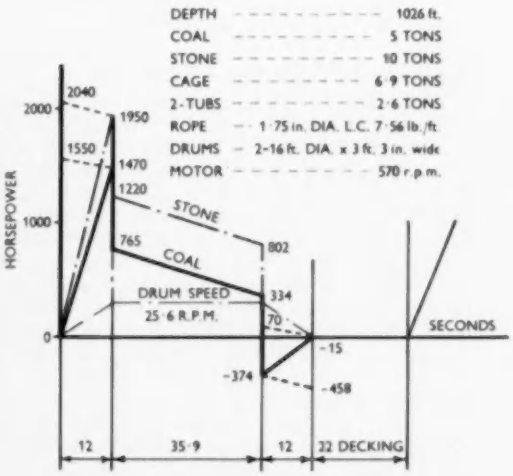



*Fig. 5.—Duty cycle for No. 2 shaft.*

FEATURES OF THE ELECTRICAL EQUIPMENT.

Many G.E.C. closed-loop speed-control winders have been installed since 1954, and these have been proved to be very successful.

The control system adopted for both the new winders at Littleton Colliery is a simplification of the original scheme and avoids the complication of an interposing electro-hydraulic servo unit. It is based upon control of torque, the driving or braking torque being a function of speed error.

maximum torque developed by the winder-motor to a predetermined value, which may be adjusted independently for winding men and coal.

CLOSED-LOOP CONTROL SYSTEM.

The winder speed is determined by the position of the driver's power lever in the slot, and is subject to slight variation due to changes of load. Speed control is effected by electrically driving or braking the winder-motor as determined by the direction of current in the

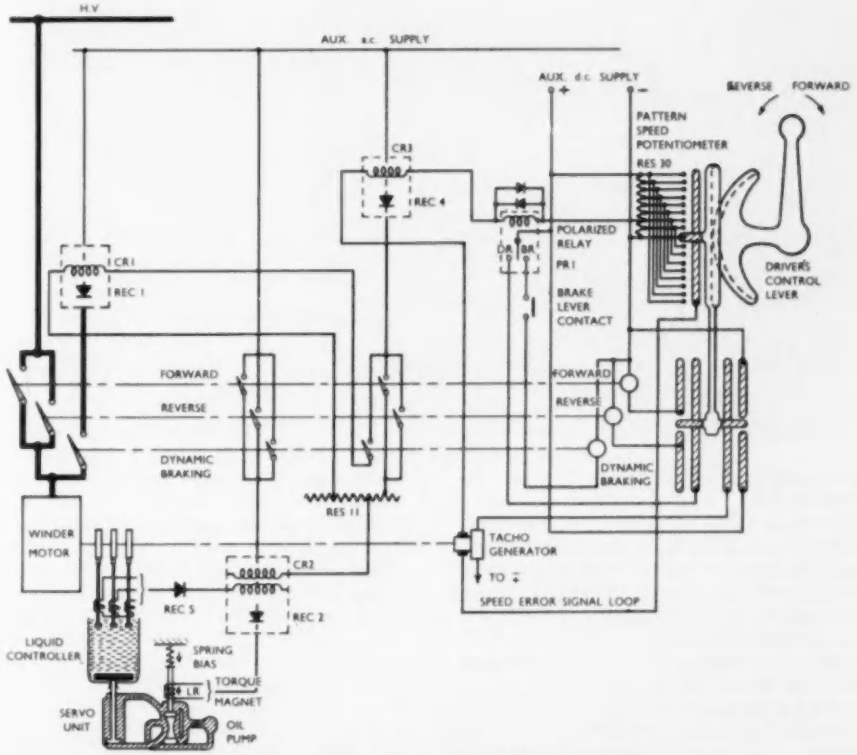



*Fig. 6.—Simplified schematic diagram of control system.*

An important advantage is that d.c. excitation for dynamic braking is fully available at standstill. Schemes which depend upon movement of the main driving machine for part of the a.c. excitation inherently involve an undesirable delay in the build-up of dynamic braking torque. The development of a reliable holding torque at very low speeds is also necessary for the precise manoeuvring of heavy loads.

Another advantage is that the system does not rely on delay mechanisms for the control of rotor-resistance, so that it is not possible to draw an excess current even if the power lever is pushed over with the brakes on. The torque-control scheme more easily complies with the statutory safety regulations, because it limits the

speed-error loop. As shown in fig. 6 this loop comprises a potentiometer operated by the driver's power lever, a tacho-generator driven from the winder-motor, the control winding of magnetic amplifier *CR*3 and a polarized relay *PR*1. The driver moves his power lever to select a voltage from the potentiometer equivalent to the speed he requires, and this is opposed by a voltage from the tacho-generator equivalent to the actual speed of the winder. The difference current is known as the speed-error, and serves firstly to operate the polarized relay *PR*1 which selects driving or braking as demanded by the direction of the error-current, and secondly to determine the magnitude of the driving or dynamic-braking current.

*Fig. 7.—Control desk for No. 2 shaft winder.*

The magnetic-amplifier *CR*3 varies the current supplied to rectifier 4 as a function of the magnitude of the speed-error signal. This function involves saturation of the output at a suitably chosen value which serves to control the maximum current that the motor can draw from the network under any conditions of operation. Under motoring conditions, rectifier 4 excites the signal winding of magnetic amplifier *CR*2, but under braking conditions, the signal windings of both *CR*1 and *CR*2 are excited.

Under motoring conditions the stator of the winder-motor is connected via the stator-reversing contactors to the a.c. supply. The torque produced is a product of the motor-flux, the rotor current and the phase-angle between them.

As the motor-flux is proportional to the applied a.c. voltage, and, since with constant rotor current the phase-angle is constant irrespective of speed, the torque developed by the winder-motor may be controlled by regulating the rotor current.

The maximum permissible value of rotor current, or any other selected value, can be maintained, independently of speed, when the current supplied by rectifier 4 is constant. This is achieved by variation of the resistance of the liquid controller in the rotor circuit. To maintain this chosen value of rotor current it is necessary to compare it with the actual rotor current and to control the movement of the liquid controller as a function of the difference between the two.

### Liquid Controller and Servo Mechanism.

The liquid controller is operated by an oil servo unit which is controlled by a rotary valve. This valve is operated by a torque-magnet opposed by a spring. When excited from magnetic amplifier *CR*2, the torque-magnet operates the valve to move the liquid controller to a lower value of resistance. If the excitation from *CR*2 is reduced to a minimum, the opposing spring overcomes the torque-magnet and forces the valve to move the liquid controller to the position of maximum resistance.

Magnetic amplifier *CR*2 has two control windings which oppose each other ; one is fed with a d.c. signal from *CR*3 which demands either an increase or a reduction in torque, and the other is the reset winding which is fed with a proportion of the rotor current from the current-transformers and rectifier 5. The characteristic of the auto-excited magnetic amplifier *CR*2 is shown in fig. 8. The total control current is the difference between the actual rotor current and the desired value as dictated by the signal current from rectifier 4. When this difference current is zero, the output from *CR*2 produces a force on the torque-magnet which just balances the spring bias of the valve, and the liquid controller remains stationary. Under steady-state conditions the torque-magnet requires constant excitation irrespective of the value of the rotor current.

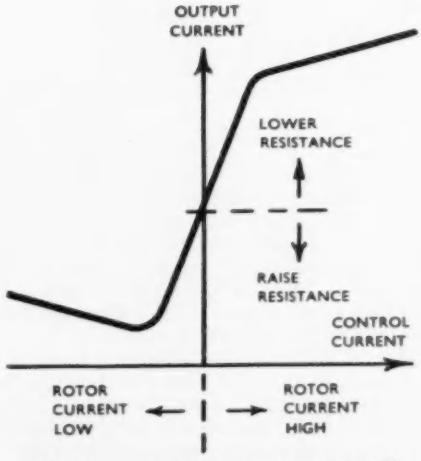



*Fig. 8.—Characteristic of magnetic amplifier CR2.*

Any increase in rotor current causing the reset winding of *CR*2 to have greater strength than the signal winding will weaken the torque-magnet and allow the spring to open the valve in the ' raise-resistance ' direction. Conversely, a reduction in rotor current opens the valve in the ' lower-resistance ' direction.

current ; for any value of d.c. excitation there is an optimum value of rotor current, and stable operation will be obtained provided that this value of current is not exceeded.

To relate the d.c. excitation to the rotor current, the output from *CR*3 and rectifier 4 is used to control amplifiers *CR*1 and *CR*2 ; *CR*1 controls the dynamic-

*Fig. 9.—Contactor control board for No. 2 shaft winder.*

DRIVING.

Consider a movement of the power lever calling for an increase in speed. The voltage from the driver's potentiometer will become greater than the voltage from the tacho-generator, and a current will circulate around the error-loop in a ' driving ' direction. The polarized relay will cause the stator-reverser to close and energize the stator for the appropriate direction of running. *CR*3 will supply a signal to *CR*2 calling for a torque to accelerate the winder-motor. *CR*2 will strengthen the torque-magnet and the liquid controller will move in a ' lower-resistance ' direction. The rotor current will rise in proportion to the torque required, or, if the speed error is large, the current will increase up to the saturation level of amplifier *CR*3. As the speed of the winder rises, the error current, and hence the *CR*2 signal current, will fall. When only driving torque is required, the rotor current, and hence the reset current of *CR*2, will fall as the speed approaches the selected speed. When the speed reaches the selected value, the signal and reset windings of *CR*2 will balance, the rotary valve will close, and the steady-state condition will obtain.

BRAKING.

To obtain optimum dynamic braking it is necessary to relate the amount of d.c. excitation to the rotor

braking excitation and *CR*2 the rotor current. Different tappings on resistor 11 are used for driving and braking, so that the rotor current can be correctly related to the stator excitation during braking.

Reverse-power braking is available in addition to the normal dynamic braking. This is applied under torque limit conditions as dictated by the rotor current and amplifier *CR*2.

EMERGENCY OPERATION.

If necessary, the hydraulic servo-gear can be controlled directly from the driver's power lever ; this is achieved by coupling the emergency linkage, which usually comprises an arrangement of hydraulically coupled transmitter and receiver units.

Under such conditions the machine operates as a simple a.c. winder, and the liquid controller assumes a definite position for each position of the power lever. No dynamic braking is available and the driver must depend upon mechanical brakes or reverse-current braking.

ACKNOWLEDGEMENTS.

Acknowledgement is due to the National Coal Board for permission to photograph the winder installations at Littleton Colliery and to publish this description of the equipment.

# Human Factors

By H. D. HOWSE, M.B.E., D.S.C., Atomic Energy Division.

*The Human Factors Section of the Atomic Energy Division is concerned with the application of the new science of ergonomics, or human engineering, to the design of complex control systems. This article outlines the various factors to be considered when planning a man/machine system and discusses man's capabilities and limitations in relation to the design of control systems. It concludes with a summary of an investigation by a firm of American research consultants into the human factors involved in the design of control rooms for nuclear power stations.*

MACHINE tools, aircraft, ships, power stations—all these are examples of systems of greater or lesser complexity where human beings and machines must, as it were, form a team for the system to function efficiently. Nowadays, the man in this team is employed less and less for his muscular strength and more and more for his ability to handle information and to make decisions.

When such a man/machine system fails, it is all too often because of some human error ; perhaps the operator failed to perceive some signal which would have told him that all was not well ; perhaps he made the wrong decision. But should the operator bear all the blame ? Did the designer of the system take full account of human capabilities and limitations ? If a mechanical component in a system fails to work, it can probably be redesigned to do the job required of it ; the human component cannot be redesigned.

The designer of a complex man/machine system, or of any part of it, has to consider and weigh up many factors—mechanical, electrical, aesthetic, economic, human. He has to take into account considerations of efficiency, safety, and many other things. Where these factors conflict—and they nearly always do—the designer must compromise.

Unfortunately, in arriving at such a compromise, the human factors do not always receive the weight they deserve. Sometimes, too, the final result is less satisfactory than it might be because the designer lacked some basic data about human beings. Where nuclear power plant is concerned, it is the effect that this may have on the safety of operation that is so important.

This article is written in the hope of fostering an interest in the human factors that affect the operation of complex systems. The subject falls into two main sections: firstly, what may be termed policy matters—which operation is best assigned to the man and which to the machine ; and secondly, a few general principles on matters of detail in the design of control systems.

In both cases, we must not only take into account Man's physical make-up but must also try and predict how he will react in various circumstances—if we can predict what those circumstances are likely to be.

## ERGONOMICS.

Even today, equipment is sometimes designed which can be operated efficiently only by a dwarf with a physics degree. This state of affairs persists largely for two reasons. In the first place each of us considers himself something of an expert on human beings ; is it not perhaps a confession of failure to call in a professional anatomist, physiologist, or psychologist ? Secondly, one of Man's virtues is that he is very adaptable ; he will learn quickly even if asked to do something that does not come naturally. Most people could quickly learn to steer a car with a wheel which acted in the opposite direction to normal—but what would be their reaction in an emergency ?

Even though earlier study of these matters would have produced obvious benefits in terms of an increase in safety, speed, and quality of work, with a reduction in mental and physical effort and training time, it required the impetus of war (coupled, paradoxically, with the increase of automation) to cause anatomists, physiologists, psychologists, and others, to join together to found the new science of *Ergonomics*—the study of man in relation to his work and environment. In America, the term *Human Engineering* is used almost synonymously, and the science is now so well established that many defence contracts in the U.S.A. lay down that man/machine systems must be examined *at the design stage* by specialists in human engineering.

Although a fair amount of ergonomic research is being carried out in universities and elsewhere, there are, so far, in the United Kingdom very few workers in this field in day-to-day contact with designers in industry. Consequently, the precise rôle that such a specialist ought to take in a design team has still to be decided. It would seem, however, that there is every advantage in including in the team someone who, in addition to supplying basic data about human beings, has the chance to stand back a pace or two and

appraise the system as a whole from the point of view of the men and women who will have to operate and maintain it.

## PLANNING A MAN/MACHINE SYSTEM.

In general, men are rather better than machines at perceiving patterns of light and sound ; improvising and using flexible procedures; storing large amounts of information for long periods and recalling relevant facts quickly ; reasoning inductively (inferring from the particular to the general) ; and exercising judgement. On the other hand, machines are better than men when it comes to responding quickly to signals ; applying great force smoothly and precisely ; performing repetitive routine tasks ; storing information briefly and then erasing it completely ; reasoning deductively (inferring from the general to the particular) ; computing ; and doing many different things at once. Men are subject to emotional stresses from which machines are free, but a proficient and well-trained man is capable of adapting himself quickly to new equipment, to sudden failure, or to a unique and unforeseen problem.[1] However, it is important to realize that Man's virtues can only be used effectively if the overall design of the system takes full account of his capabilities and limitations. It is the function of the ergonomist to advise designers on these human considerations.

One of the larger differences between the designs of the nuclear power stations at Calder Hall and, say, Hunterston is that the overall control of the latter is largely automatic. This is mostly because the minute-to-minute controlling of the latter type of reactor may well be beyond the capabilities of a human operator. But automation throws up its own problems, particularly where vigilance is concerned. The responsibilities of the crew of the control room now become largely supervisory : firstly, they must ensure that the automatic equipment continues to function as it should ; secondly, they must be ready to take control in the event of breakdown—if the reactor has not shut itself down meanwhile.

How can we ensure that the operators, after perhaps many months or even years of uneventful shifts, will in an emergency first of all perceive that something is wrong and then take the right action ? A few of the factors to be considered are as follows :

(*a*) It has been proved that, to keep alert, it is more or less essential for the mind to be given some work of a reasonably varied nature.

(*b*) To do the right thing in an emergency requires a reasonable level of intelligence ; but monitoring jobs are more boring to an intelligent man than they are to others.

(*c*) There is some evidence[2] that personality may affect a man's watchkeeping capabilities.

(*d*) The more the operator is ' in the picture ' when something happens, the more likely he is to do the right thing. But again, boredom and monotony make it unlikely he will be able to be right up to date on the state of his plant.

The principles are clear : find the right kind of man (or woman) for the job, give him the right tools, and train him so that he knows what he ought to do. But when we start considering the problem in detail we realize that there is much we do not know.

## CONTROL SYSTEMS.

Let us now look more closely at some of the factors that must be considered in the layout and design of control systems. In the paragraphs that follow, the term ' indicator ' includes auditory signals such as bells and hooters, as well as visual displays such as dials, lights, mimics, cathode-ray tubes, and illuminated annunciators. So far, except in the shape of controls, the senses of touch and smell do not seem to have been used in this field, though they have been used for many years by engineers in fault-finding.

### Signal-to-Noise Ratio.

The first requirement is that the signal requiring action should be detected by the person for whom it is meant. The signal—visual, aural, or otherwise—must stand out from the background ' noise ', which here includes other signals that at the moment have less priority. At some traffic roundabouts there are so many road signs that the one signal that the motorist may want to perceive—which exit to take—is often difficult to distinguish. Also, the motorist who is not actually seeking information often perceives none of the signals intended for him. Ideally, the signal that is relevant at a particular moment should be in the centre of the receiver's perceptual field. Though this is almost impossible to achieve in practice, much can be done by laying out display systems in a logical and systematic manner and by differentiating the various signals by the use of the different senses—using colour, size, shape, etc.

### Frame of Reference.

Because the human being is poor at absolute judgement but good at making comparisons, he will do best if he is given a pattern or frame of reference against which to compare incoming information. Give a man a cake, ask him to estimate its weight, and his success

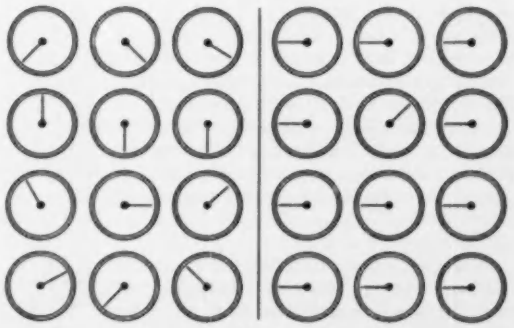


*Fig. 1.—Improvement brought about through realignment of check-reading indicators. With the improved layout (right) a pointer showing an unusual reading is easily noticed.*

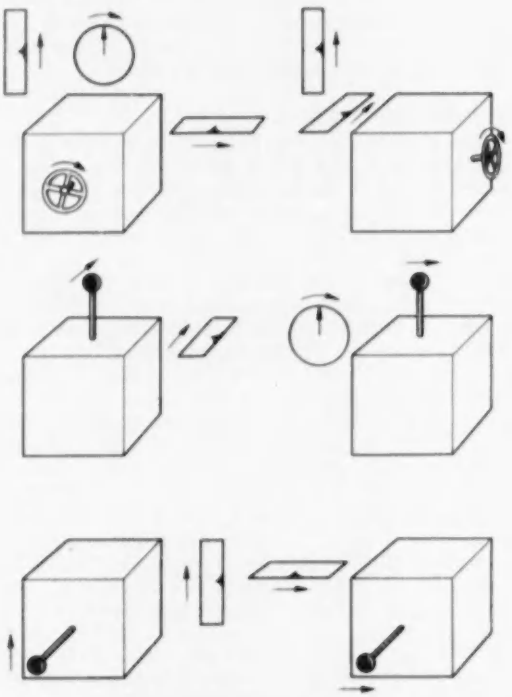


*Fig. 2.—Illustration of compatible movements between controls and indicators.*

or otherwise will depend more upon chance than skill. Ask him which of two cakes is the heavier and his chances of success will improve enormously. Another example of the application of this principle is the aligning of visual check-reading indicators so that when all pointers are in line at, say, 9 o'clock, all is well. This is illustrated in fig. 1.

### Limit of Short-term Memory.

While Man's long-term memory (the storage capacity of the brain) is very large, his short-term memory is poor, particularly when he is trying to remember a large number of very similar items. If you continually rehearse it, you may remember a number like 990900990—until your attention is distracted. If information is presented before it is needed, there is a risk of its being lost before it can be used. Cursors, graphic recorders, and even the humble pencil and paper, are examples of things that can help.

### Controls.

The importance of having a control handy to the indicator that it affects is often forgotten. Another point is what is sometimes known as control/indicator compatibility. If a control is turned clockwise, pushed upwards, or to the right, one usually expects the associated pointer to move clockwise, upwards, or to the right, and the quantity being controlled to increase, move upwards, or to the right. Fig. 2 illustrates this. Many accidents have been caused where stereotypes such as these have been disregarded.

### Conventions.

Where convention affects the ergonomic layout, great care is needed. For example, in this country we read across the paper in lines from left to right and down the page from top to bottom; we therefore naturally scan a control panel in the same sequence. In some countries, however, they read lines from right to left or from top to bottom. In British electrical practice, the convention is 'down for on'; in aircraft cockpits, on much electronic apparatus, and more generally in many other countries including the U.S.A., one presses down to switch *off*. A failure to standardize units of measurement raises similar operator problems; probably the most familiar is the use of both Centigrade and Fahrenheit temperature scales on different instruments in the same control position.

### Appearance.

In panel layout it is unfortunately true that aesthetic and ergonomic considerations are not always compatible, the symmetry so beloved by appearance designers being the most frequent cause of disagreement. In the recently-superseded model of a popular family car all the switches except that of the direction indicator were placed in two neat rows in the centre of the facia panel (fig. 3). This arrangement had a number of disadvantages:

(*a*) the driver had to lean forwards and sideways out of his driving position to operate all but the closest switches;
(*b*) when the driver had his eyes on the road, it was easy to operate the wrong switch, because these were close together and mostly the same shape;
(*c*) it was not easy to tell on sight whether the switches were 'on' or 'off'.

The lower photograph shows that on the new model the corresponding switches have been so disposed that:

(*a*) they are more accessible to the driver;
(*b*) they are more spread out and thus much easier to find by 'feel';
(*c*) the replacement of some push-pull switches by toggle switches gives a much more positive control.

What has happened, of course, is that the signal-to-noise ratio is now greater, and a better frame of reference has been provided.

### Layout.

When laying out a control system, it is essential that the designer should consider *in detail* the different tasks the operator will have to perform. He must have a thorough knowledge of the *type*, *amount*, and *accuracy*, of the information required. The display should not contain more than is necessary, nor should it be more accurately displayed than the limitations of the rest of the system warrant.[3]

It may be possible so to group indicators and controls that those concerned with operations that do not happen very often (such as starting up) are clear of those required for normal operation (that is, for monitoring the steady state). This would improve the signal-to-noise ratio of the latter indicators, including the warning and alarm systems. Indeed, duplication of some indicators may well be acceptable if it would facilitate such grouping. With each group, the main principles governing the layout ought to be :

(*a*) that the important indicators should stand out from the less important ones ; and

(*b*) that the ultimate operational sequence of using the instruments should be considered.

The second principle is illustrated in fig. 4, which shows the flow diagrams for the original and revised designs of an instrument panel.

*B.M.C. Photograph*

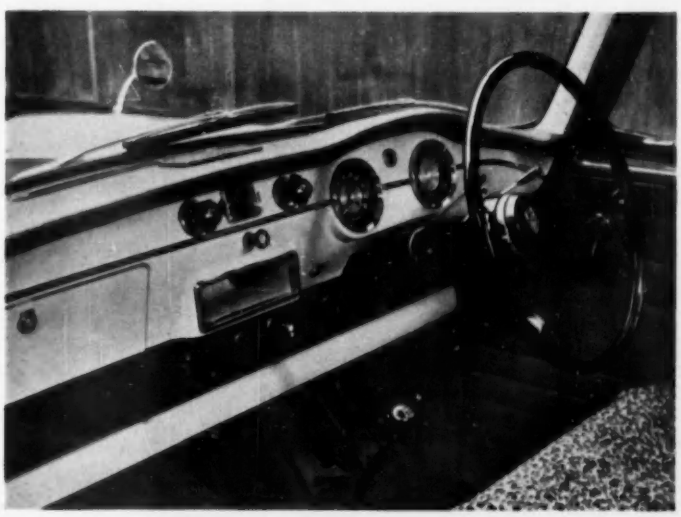


*Fig. 3.—Improvement in the disposition of switches on a family car: (above) earlier model; (below) later model.*

## CONCLUSION.

The complexity of nuclear power stations offers a new and challenging field for the ergonomist. The Human Factors Section of the G.E.C. Atomic Energy Division has passed the beginning of its study of the problems. It is now progressing from the stage of commenting on existing designs to a closer association with the plant while it is still on the drawing board.

In this article, it has only been possible to touch on a few general principles of part of this subject. Fault-finding, repair, maintenance, human relations, welfare, environmental problems, personnel selection, manning, training, written instructions —none of these have been mentioned although they are all very relevant.

If equipment can be so designed that it can be operated efficiently by the unskilled with the minimum of instruction, so much the better. Man may not be very good at keeping watch but would it be possible to design a machine so versatile and adaptable that it could sweep the floor, write up the log, smell a fire, *and* take the right action in an unforeseen emergency ? It is doubtful. Let us try and make the best use of Man's strong points and help him in his weak ones.

## APPENDIX.

Since the preceding article was written, a team of research consultants has carried out a study of the human factors involved in the design of control rooms of nuclear power stations.

All the members of the three-man team had expert knowledge of human capabilities and limitations and all had considerable experience in analysing large and complex control systems from the point of view of the men who have to operate them. It was hoped that this investigation would not only lead to direct benefits—in the form of design recommendations which would be of value both now and in the future —but would also give extremely valuable indirect help by allowing the methods of analysis used by these

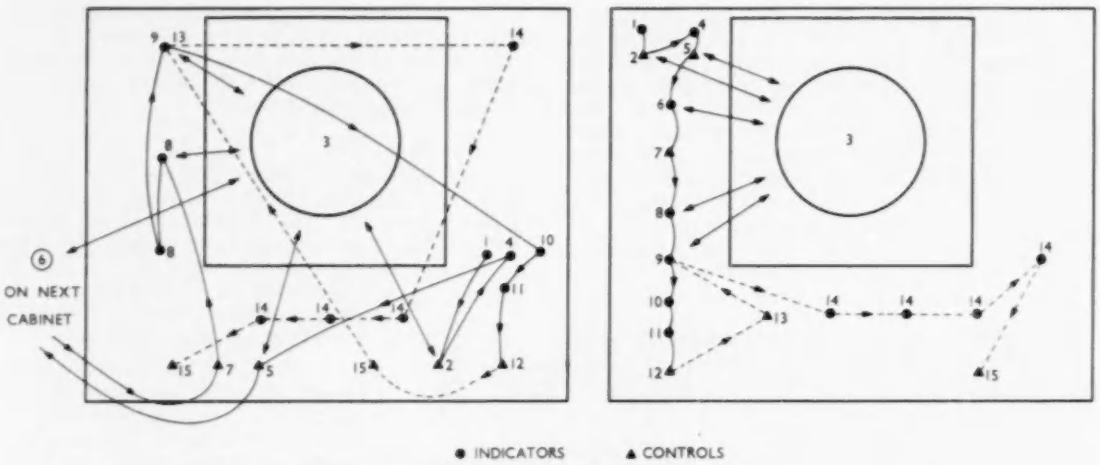



*Fig. 4.—Original (left) and revised (right) versions of an instrument panel, showing the sequence of use of controls and indicators.*[4]

experts, and their approach to such problems, to be observed at first hand.

THE ANALYSIS.

The approach taken by the consultants is that such analyses should be system-oriented ; the man must not be considered alone but only within the context of the man/machine system. The following quotation from the team's original proposal emphasizes this point :

' The main aim of this analysis will be to achieve a design of the man/machine system so that system performance is optimized. Optimization is understood to include not only the achievement of the desired product, but also such factors as safety, comfort and economy. Our major effort will be directed at the man/machine interface so as to ensure that :

(1) All ' cross-talk ' between men and machines (and where necessary between men) may be conducted quickly and accurately.
(2) All environmental conditions will be controlled in order to enhance the efficiency and comfort of operator personnel.'

For such an approach to be effective, a considerable amount of analysis is needed before settling such details as knobs and dials. First it is necessary to identify beyond doubt the aims of the system as a whole ; only then is it possible to consider what role Man can best play in the system. As has been discussed in the preceding article, some functions are performed more efficiently by human beings, others by machines. For example, Man is an outstanding performer as a decision-maker whereas a machine will usually keep a better watch and be a more efficient continuous controller.

By taking these factors into account, it is possible to decide which functions in the system should be performed by human elements and which by machine elements. Then, at last, it is possible to decide what tools Man needs to perform these functions most efficiently.

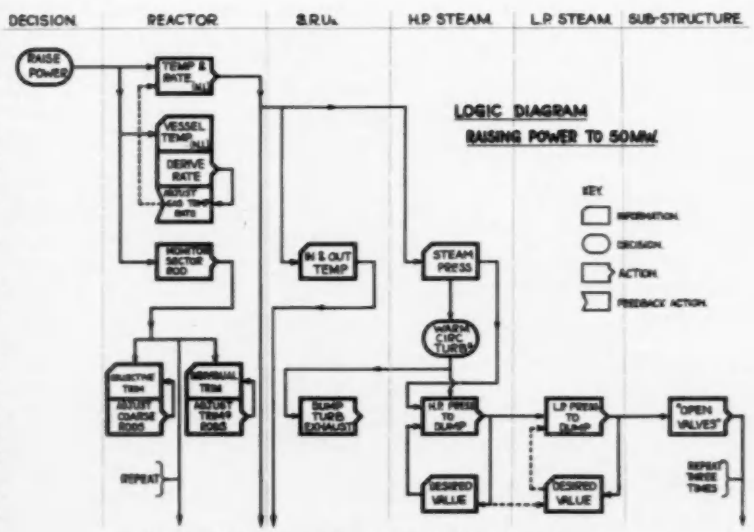



*Fig. 5.—Section of an information/decision/action diagram.*

THE DECISION DIAGRAM.

This preliminary work required methodical and detailed analysis, and one of the more interesting analytical tools used was the information/decision/action diagram, sometimes called a logic diagram. Fig. 5 shows in abbreviated form a section of one of these diagrams. A man has to acquire information in order to make decisions; the decisions must be implemented by actions. If such a diagram is made out for each operation the man has to perform, it makes it easier:

(*a*) to ensure that a proper and a complete understanding of the system has been achieved;

(*b*) to indicate the roles of the operators and to make some assessment of the rate of incoming information, the complexity of the decisions needed and type of actions required in response to these decisions;

(*c*) to decide what displays and controls are needed.

The amount of detail required on such diagrams depends upon their immediate purpose. In the early stages of formulating design concepts, only broad-brush treatment may be needed, but assessing the adequacy of displays and controls in existing systems may demand a very detailed diagram.

THE RESULTS.

The recommendations fell into two main classes. The first of these amounted to a constructive criticism of existing designs. Here, the suggestions made assumed that existing design concepts should be adhered to and that the only changes permissible would be those which involved no major redesign and which could, in the majority of cases, be implemented by 'off-the-shelf' items of equipment. The second major grouping was called the 'Blue Sky' system. Here, the team assumed that they were quite free of existing designs.

The report recommended that the human-factor design concepts should be based on the following rules:

(1) *Leave primary safety functions to machine elements.* Consider the man only as a final safety device.

(2) *Man's primary role should be that of decision-maker.* Even then, unimportant routine decisions which can be foreseen should be left to machine elements.

(3) *Do not use him as a continuous controller,* as an amplifier or transducer in a control loop. Nevertheless, he must have the facilities to allow him to enter control loops in an emergency.

(4) *Alert him as early as possible to fault or potential fault conditions.* Except where ultimate safety would be jeopardized, give him the flexibility to decide at what level he should be alerted and allow him to override the automatic control system.

(5) *Do not ask him to keep a continuous watch.* As far as possible, monitoring should be automatic.

In fact, existing design concepts differ very little if at all from those enumerated above. Beyond this, it is not possible to publish the results of the study at this stage, except to say that the report discussed a very wide range of subjects—alertness, monotony, boredom, decision-making, training; deviation, derivative, predictive, analogue, digital, patterned, 'on demand' and feedback information; check-reading, flexibility, compatibility, standardization, the hierarchical structure—to mention but a few.

G.E.C. personnel at the Applied Electronics Research Laboratory at Browns' Lane, Coventry, have recently completed for the Admiralty a human factor study using much the same techniques, although the subjects of the study were different in the two cases—in the one the study concerned a nuclear power station, in the other a warship. It is interesting to note that the two teams, working quite independently, made very similar recommendations on some matters where both considered that existing practice was wrong.

The more complex a man/machine system becomes, the greater the load that tends to fall upon the human elements in that system. This by-product of the enormous technical advances that are now being made is surely one of today's greater problems.

Man has certain skills which have not so far been reproduced in machines. For the very complex control systems now being developed, it is only if systematic studies such as have been described are carried out that these skills can be used to the best advantage to promote the efficiency of the system as a whole.

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# Developments in Power Rectifiers

## 4. LOW-VOLTAGE RECTIFIERS

By L. J. C. CONNELL, B.Sc., A.Inst.P., Research Laboratories.

THE low-voltage power rectification field is defined, for this article, as covering voltages up to 250 V and currents of 50 A or more. Power supplies with d.c. outputs within this range are used for a variety of applications, the more important of which are listed below :

**Applications for low-voltage rectifiers**

| Electrolytic | Others |
|---|---|
| Electrolytic cleaning | Motor drives |
| Electro-plating | Welding |
| Anodising | Arc furnaces |
| Cathodic protection | Arc lamps |
| Battery charging | Electromagnets |
| Electrolytic production of gases (hydrogen, oxygen, chlorine) | Excitation of alternators |
| Electrolytic extraction and refining of metals | General purpose factory supplies |

### RECTIFIERS FOR LOW VOLTAGES.

In the low-voltage field, many different types of rectifier have been used : aluminium and tantalum electrolytic rectifiers ; polycrystalline solid-state rectifiers based on cuprous oxide, cupric sulphide and selenium ; single-crystal germanium and silicon rectifiers ; mercury arc rectifiers ; mechanical contact rectifiers. Other types are at present being studied—for example titanium dioxide, silicon carbide and gallium arsenide—but in general, the interest in them arises less from the promise they show as industrial power rectifiers than from special characteristics (such as the ability to operate at high temperatures) which make them attractive for specialized military applications.

For the last 15-20 years, the selenium rectifier has been used much more extensively than any other in the low-voltage field. It superseded the copper oxide rectifier in power applications because of its smaller size, higher operating temperature and better reverse voltage rating. Except at the upper end of the voltage range, the mercury arc rectifier is seldom used ; no advantage can be taken of its high peak inverse voltage rating, and its low efficiency at low voltage (which results from the high voltage drop in the forward, or conducting, direction) puts it at a disadvantage. The contact rectifier is essentially a high-current rectifier. It has not been used much in this country but is used on the Continent and, on a more limited scale, in the U.S.A., in electrolytic work at currents of 10 000 A or more. The germanium and silicon single-crystal rectifiers are the most outstanding rectifier developments of recent years. They are suitable for use not only at all voltages and currents in the range now under consideration but also in a wide field outside it. Of the other types, the electrolytic rectifiers are now obsolete ; the copper sulphide rectifier has found no more than limited use, mainly in the U.S.A. and at voltages up to 10-15 V.

The general picture today, therefore, is that the selenium, germanium and silicon rectifiers are types which must be considered for applications throughout the low-voltage range, with mercury arc rectifiers and contact rectifiers (both of which were described in the article forming Part 3 of this series) of possible interest for voltages of 200-250 V and for currents greater than 10 000 A.

In the following sections, descriptions are given of the construction and characteristics first of the selenium rectifier and then (in more detail) of germanium and silicon rectifiers. Finally, some general comments and comparisons are made.

### SELENIUM RECTIFIERS.

The selenium rectifier[1-8] is a plate-type rectifier in which the rectifying barrier is located at the interface between a polycrystalline selenium coating on a sheet-steel or aluminium support and a counter-electrode alloy deposited on the selenium (fig. 1).

Although the theoretical principles underlying the operation of the rectifier have received much study, they are still imperfectly understood. Manufacturing techniques have evolved empirically and there are, in general, no satisfactory explanations for the marked effects on electrical characteristics of minor additions of selected impurities or small changes in processing techniques.

There are several different processes for preparing selenium rectifier plates. In principle, they involve :

(*a*) preparing the surface of the base-plate by shot-blasting or etching and sometimes also by cladding with nickel or bismuth;

(*b*) applying a layer of amorphous selenium (often containing a halogen additive) by spreading the material as a powder, or by deposition in vacuum;

(*c*) heat treating the selenium to convert it to polycrystalline form, followed sometimes by chemically treating the surface;

(*d*) applying a low-melting counter-electrode alloy, e.g. the bismuth-cadmium or the tin-cadmium eutectic;

(*e*) ' forming ' the plate by passing current through it in the reverse direction for a considerable time.

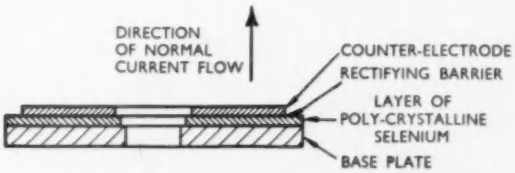


*Fig. 1.—Construction of a selenium rectifier plate.*

After the plates have been tested, they are assembled in stacks (fig. 2) and connected in series, parallel, or series-parallel to give the desired output. The heat generated by power lost in the rectification process may be dissipated by any of the usual cooling methods : natural-air cooling, forced-air cooling, oil-cooling, or water-cooling.

Developments during recent years have taken the form of successive small improvements directed towards enabling operating temperatures, forward current ratings and reverse voltage ratings to be increased and ' ageing ' (the progressive increase during life of the forward volt-drop) to be reduced. Ageing has been a difficult problem to tackle because it is essentially a long-term effect and cannot be simulated reliably by accelerated testing. It proceeds more rapidly at higher operating temperatures and since it causes increased power generation in the plate (and hence increased plate temperature) the effect is cumulative.

For general industrial duty, most manufacturers now offer plates with peak inverse voltage ratings of 35-40 V. The ratings are often quoted in terms of maximum r.m.s. a.c. input voltages, i.e. 25-28 V r.m.s. Maximum plate temperatures during normal operation are usually 70-85° C. Different manufacturers quote different working current densities and current ratings depend also on the cooling method in use. In general, mean operating currents are within the range 30-150 mA per $cm^2$ of effective plate area.

Two rectifier circuits used extensively with selenium, germanium and silicon rectifiers are shown in fig. 3. The six-phase star (or three-phase centre tap) circuit is used at low voltages, where the required d.c. output can be obtained without series connexion of rectifier elements. Each rectifier element, during the period when it conducts (i.e. one-sixth of each cycle), carries the full d.c. output current. The effective forward voltage drop in the rectifier circuit is therefore the voltage drop which occurs in an element when it is carrying six times its mean current. For the three-phase bridge circuit, the total effective volt-drop is that due to two elements in series, each carrying three times its mean current. For selenium rectifiers, with some allowance made for ageing, typical values for effective volt-drop are 1·3-1·5 V per series plate. A mobile selenium rectifier equipment for supplying power for servicing aircraft is shown in fig. 4.

## GERMANIUM AND SILICON RECTIFIERS.

### *P-* AND *N-*TYPE SEMICONDUCTORS.

In germanium and silicon rectifiers, rectification takes place at junctions between differently doped regions (*p*- and *n*-type) formed in discs cut from single crystals of the semiconductor materials. Using silicon as an example, a simplified outline of the principles of diode construction and operation is given below. More detailed information may be obtained from the selected references to the extensive literature.

Doping of silicon to form an *n*-type region in a crystal is achieved by the addition of phosphorus, arsenic or antimony. When an atom of one of these impurity elements takes the place of a silicon atom in the crystal lattice, only four of its five valence electrons are used in forming bonds with neighbouring silicon atoms. The fifth is relatively free to move through the lattice. If an electric field is applied across a silicon crystal which has been doped in this way, the movement of the ' free ' electrons introduced via the

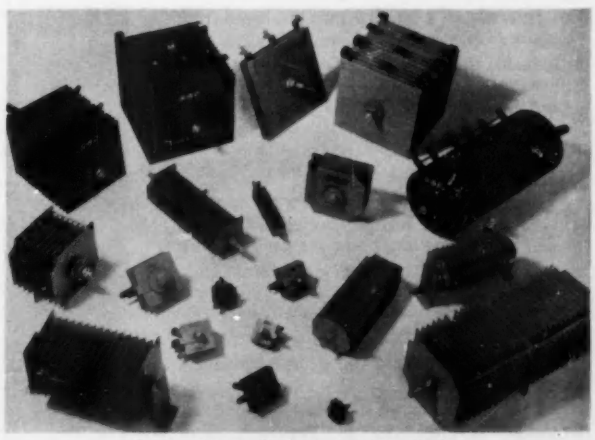

*Fig. 2.—Group of selenium rectifier stacks.*

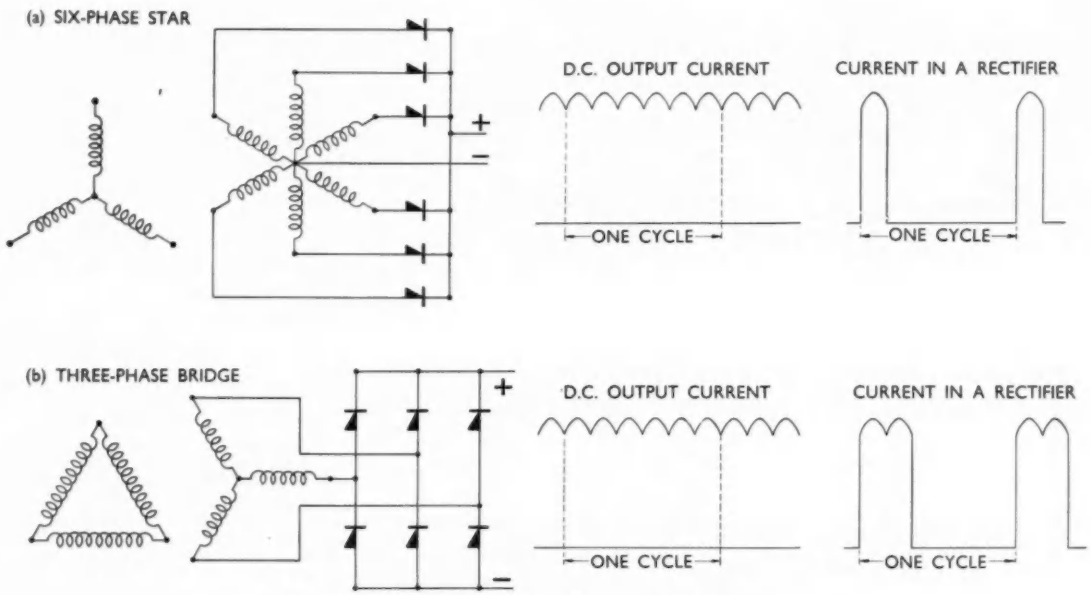


*Fig. 3.—Rectifier circuits and current wave-forms.*

impurity element gives rise to a flow of current. Thus the addition of the impurity element reduces the resistivity of the silicon and since the added charge carriers are electrons, which have *negative* charges, the silicon is described as *n*-type. The element which introduces the electrons is called a *donor* impurity.

When boron, aluminium, gallium or indium (each of which has three valence electrons) is introduced, there is a local deficiency of one electron at each lattice site occupied by an impurity atom. An electron from a neighbouring bond can move in to fill this vacancy and in moving, it in turn leaves a vacancy, or ' positive hole ', which can be filled in a similar manner by an electron from another bond. In the presence of a field, a current flows and since the current is associated with the migration through the crystal of *positive* holes the silicon is said to be *p*-type. The added impurity is called an *acceptor*.

### *P-N* JUNCTIONS.

*Bulk Properties*[2, 3, 5, 9-12].

The *p-n* junction in one widely used type of silicon diode is formed between a highly doped *p*-region and a lightly-doped *n*-region in a disc of single-crystal silicon (fig. 5). At such a junction, in the absence of a field, there is a tendency for some of the excess holes to diffuse from the *p*- to the *n*-region and some of the excess electrons from the *n*- to the *p*-region. These migrations affect the charge distribution near the junction, leaving the *p*- and *n*-regions negatively and positively charged respectively. A space-charge region is thus established across the junction and a potential barrier is set up which opposes further diffusion of carriers. For the type of junction considered, most of the space charge region is at the lightly-doped (*n*-type) side.

If the *p*-region is now made positive with respect to the *n*-region, the potential barrier decreases. The junction is now biased in the forward or conducting direction ; holes begin to pass from *p*- to *n*- and electrons from *n*- to *p*-regions and a current flows. This current increases with increase of applied voltage and when the voltage passes the point where the

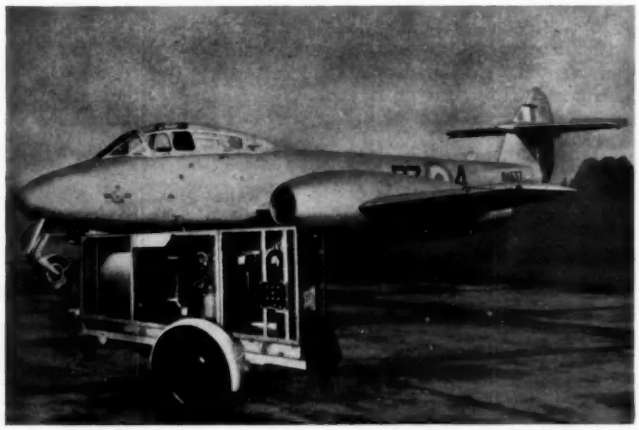

*Fig. 4.—Mobile selenium rectifier equipment, with inspection covers removed.*

potential barrier has been overcome, the current increases very rapidly (fig. 5*b*).

If, on the other hand, the *p*-region is made negative with respect to the *n*-region, the space-charge region widens, the potential barrier at the junction increases and it becomes extremely difficult for holes from the *p*-region to enter the *n*-region or for electrons from the *n*-region to enter the *p*-region. It might be expected that the current under these conditions, with the junction connected in the reverse or blocking direction, would be zero but in fact some current flows. This results from the movement, under the influence of the field, of:

(*a*) minority carriers (electrons from *p*- to *n*- and holes from *n*- to *p*-regions) formed by thermal breaking of electron bonds and the consequent establishment of electron-hole pairs in both *p*- and *n*-regions, and

(*b*) electrons and holes produced by the generation of electron-hole pairs in the space-charge region[11, 13-16].

Both these charge generation processes are temperature-dependent, (*a*) increasing more rapidly with temperature than (*b*). For silicon diodes, at temperatures below about 200° C, most of the reverse current in the bulk material is probably due to space-charge generation. The rate of generation is less the higher the carrier lifetime in the silicon. At a given temperature, the space-charge generated current increases with voltage (theoretically, in proportion to $V^{\frac{1}{3}}$ for a step junction and to $V^{\frac{1}{2}}$ for a graded junction). If the reverse voltage is increased progressively, the field in the space-charge region increases, and eventually electrons and holes, in passing through the region, acquire sufficient energy to enable further electron-hole pairs to be produced when they collide with valence

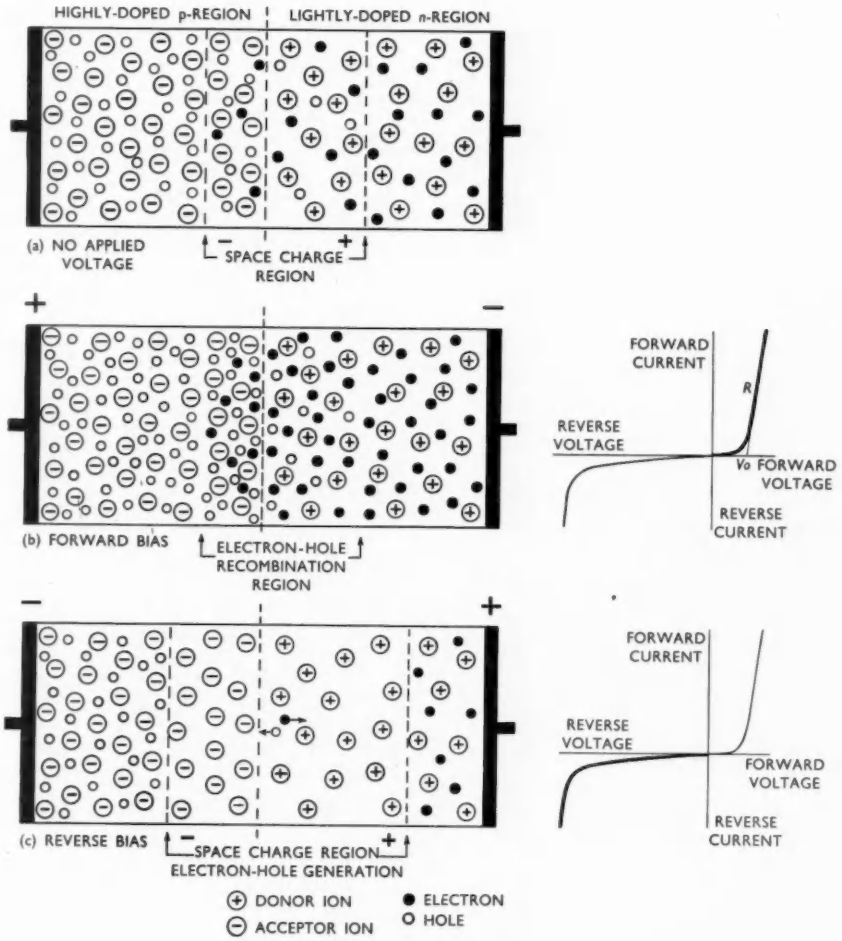


*Fig. 5.—Rectification at a p-n junction.*

electrons of atoms in the lattice. These additional carriers contribute to the conduction process—i.e. current multiplication sets in and the junction rapidly enters the breakdown condition[11, 17-21].

*Surface Properties*[22-27].

So far, consideration has been given only to conditions within the bulk semiconductor material. Conditions at the surface in the vicinity of the junction can have a very marked (but as yet less predictable) influence on the reverse voltage-current characteristic of the junction.

The atoms at a clean silicon surface are attached, by some of their bonds, to atoms within the lattice but, since the surface atoms are at the end of the lattice they have other dangling unfilled bonds, each of which is capable of accepting an electron and thereby causing its parent atom to become negatively charged. The surface is therefore strongly $p$-type[26, 27]. At a $p$-$n$ junction, an atomically clean surface of this kind would be unacceptable since it would provide a low-resistance $p$-type shunt path across the junction.

Because of the presence of unfilled bonds, an atomically clean surface has a great affinity for foreign atoms. Such atoms can completely alter the character of the surface and can affect the nature and stability of the reverse characteristic of a junction. Impurities present in amounts occupying less than a monolayer may have a pronounced effect ; inner and outer regions of a multi-layer coating may respond at different rates to junction field changes ; ions at the surface may migrate under the influence of the field. Water vapour and oxygen are two common materials which have marked effects on germanium and silicon surfaces.

The junction surface treatments used during the fabrication of power diodes are determined empirically. They are selected to produce an acceptable compromise of compatibility with the differently doped regions a the two sides of the junction. Often, they involve chemical or electrolytic etching, washing, exposure to selected atmospheres, and heat treatment.

## Design Principles for Rectifying Junctions in High-power Diodes

A silicon power diode should preferably have a high breakdown voltage, a low reverse current and a low forward volt-drop. To obtain the high breakdown voltage, high resistivity (i.e. very lightly doped) silicon must be used. Unfortunately, the reverse current at a given voltage increases with increase of silicon resistivity (theoretically as $\rho^{\frac{1}{2}}$) but the current decreases with higher carrier lifetime in the silicon.

In the forward direction, the volt-drop has two components : the threshold voltage $V_0$ (which is an inherent property of the semiconductor material and is higher for silicon than for germanium) and the resistive portion $R$ (fig. 5*b*). The resistive drop can be kept to a minimum by using silicon of high lifetime, by arranging that the width of the lightly doped region, whilst adequate to give a high breakdown voltage, is not excessive, and by providing (with the $p^+n$ design under consideration) a highly doped $n^+$ region at the base electrode. Under these conditions, strong carrier injection from both $p^+$ and $n^+$ regions during forward conduction ensures a low forward volt-drop despite the high resistivity of the lightly doped $n$-region.

Clearly, in making a diode, the quality of the semiconductor crystal is of paramount importance ; a low impurity content and good crystal perfection are essential. High-grade germanium has been obtainable for a few years, and latterly much progress has been made with the more difficult problem of producing ultra-pure silicon. Intrinsic material is not yet available. The most obstinate impurity is boron (which is $p$-type) and the best silicon obtainable today is $p$-type with a resistivity of about 1000 ohm cm. In principle, this material could be counter-doped with an $n$-type impurity to give $n$-type crystals of equally high resistivity which would be equally suitable for use in high-power diodes. In practice, it is not easy to do this. The residual boron is evenly distributed throughout the silicon but the compensating $n$-type impurities tend to be distributed less evenly, with the result that it is difficult to make crystals of uniformly high resistivity from compensated silicon. Moreover, the process of introducing the compensating impurities usually involves additional operations. There is a trend today towards the use of $p^+$-$i$-$n^+$ structures[9, 11, 28, 29] in which the $i$ (nominally intrinsic) region is in fact very high resistivity $p$-type silicon, the rectifying junction being located at the barrier between this and the $n^+$ region.

## Practical Designs of Diode Construction and Characteristics.

Some practical large-area germanium and silicon diodes are shown in fig. 6 and their internal constructions in fig. 7. All have junctions 2 cm² in area.

The junctions in most of the high-power diodes available today are prepared by alloying processes. The germanium diode and one of the silicon diodes in fig. 7 are of this kind. A disc of the alloying material is placed in contact with a disc of single crystal semiconductor and the assembly is heated so that the alloying material melts and takes some of the semiconductor into solution. During subsequent cooling,

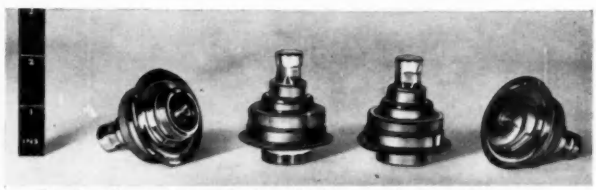

*Fig. 6.—Germanium and silicon high-power diodes with junctions 2 cm² in area.*

*(a) Left-hand pair, water-cooled.*

*(b) Right-hand pair suitable for clamping to fins for air- or oil-cooling, or to liquid-cooled plates.*

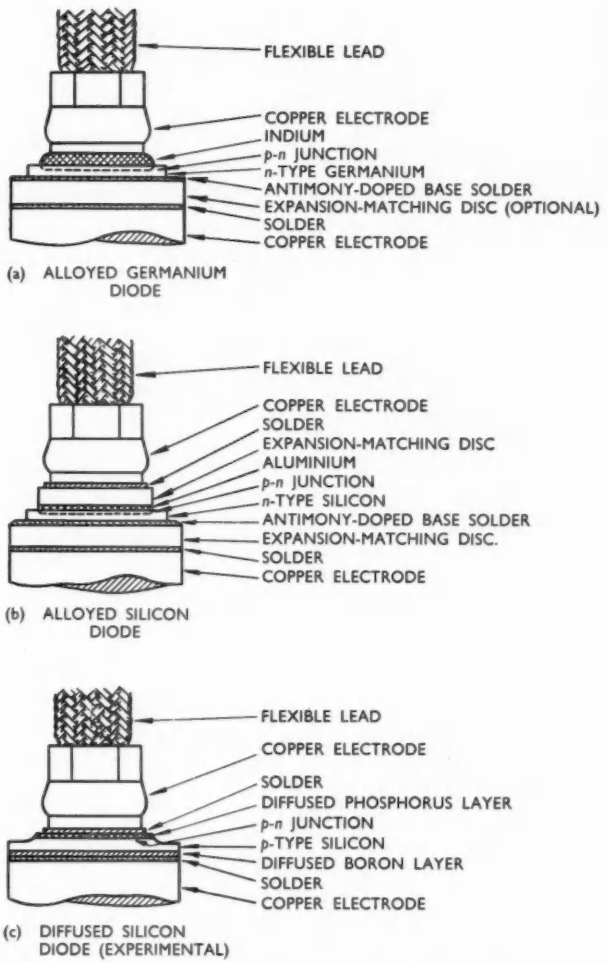


*Fig. 7.—Internal construction of high-power diodes.*

the semiconductor crystallizes back and the rectifying junction is formed at, or just below, the interface between the recrystallized region and the parent semiconductor. In silicon diodes, there is usually a considerable expansion mismatch between the alloys formed at the two surfaces and the silicon of the parent disc. To minimize stresses, it is usual to back the silicon on one or both sides with expansion-matching discs. The solders for attaching these discs to the electrodes must be chosen to withstand the temperature fluctuations they will experience during service. In germanium diodes, where indium (a very soft metal) is almost invariably used as alloying material and tin/lead as base solder, and where operating temperatures and temperature fluctuations are lower, expansion-matching discs are not essential.

The junction and the highly doped *p*-type base region in the second silicon diode are both prepared by diffusing-in the appropriate impurities at temperatures of 1200-1300° C.

To those inexperienced in semiconductor technology, these high-power diodes sometimes appear deceptively simple to manufacture. In fact, in the alloyed silicon diode in fig. 7(*b*), there are no fewer than fourteen separate layers present initially as discs or plated coatings (i.e. not counting alloy layers produced during junction formation or electrode attachment) between the two copper electrodes. At all interfaces, good wetting and contact between adjacent layers are essential and close control must be maintained over the uniformity and extent of alloy penetration. To avoid risk of contamination of junction surfaces, no fluxes are used during the preparation of the junctions, or the attachment of the junctions to the electrodes, or at any other stage during manufacture.

The diodes have ceramic-metal cases in which all joints are made by high-temperature brazing or by welding. These cases provide hermetic sealing for the junction, are mechanically robust and are well able to withstand temperature cycling and thermal shock. Typical forward and reverse characteristics for the three diodes are shown in fig. 8.

With germanium and silicon diodes, the heat generated at the junction (nearly all of which is attributable to power loss during forward conduction) must be dissipated in such a way that the junction is held at a safe temperature—i.e. a temperature at which the diode has a long life. If ability of the diode to operate under steady conditions were the sole requirement, maximum junction temperatures during normal operation could usually be somewhere in the range 70-100° C for germanium and 130-200° C for silicon. Other requirements, discussed later, often necessitate lower temperatures.

For the germanium and silicon diodes in fig. 8, power losses amount to 0·5-0·6 and 0·9-1·2 watts per ampere respectively when the diodes are operated at mean currents of 100-150 A in a three-phase bridge circuit (300-450 A d.c. output from the bridge). Any of a number of cooling methods may be used for removing heat from the junctions. For example the diodes at the right in fig. 6 may be clamped to fins which are air-cooled by natural or forced convection or oil-cooled, or they may be clamped to water-cooled or oil-cooled busbars. Those at the left are used in association with special water-cooling heads (fig. 9) which provide particularly rapid heat transfer at low water-flow rates.

The effectiveness of the cooling system of a diode is often expressed in terms of the difference between the temperature of the junction and that of some selected point in the cooling system for unit power input to the junction (°C per watt). This quantity is known as the

thermal impedance of the part of the system under consideration. For the diodes in fig. 6(*b*) the thermal impedance from junction to base is about 0·2° C per watt (it varies a little with the make-up of the junction structure).

Table 1 gives figures for the overall thermal impedance (junction to air) for alloyed-junction silicon diodes mounted on representative extruded aluminium fins and cooled naturally and by forced-air.

Fig. 10 shows the performance of a water-cooled silicon diode of the kind illustrated in fig. 9. By virtue of the turbulent flow conditions on the internal surface of the base electrode and the close proximity of this surface to the junction, an overall thermal impedance (junction to water) as low as 0·25° C per watt is obtained at the low water-flow rate of 1 litre/min. This construction provides much better cooling of the junction than can be obtained by clamping diodes to water-cooled plates. For a diode carrying 200 A, the temperature rise of the cooling water at 1 litre/min is under 4° C.

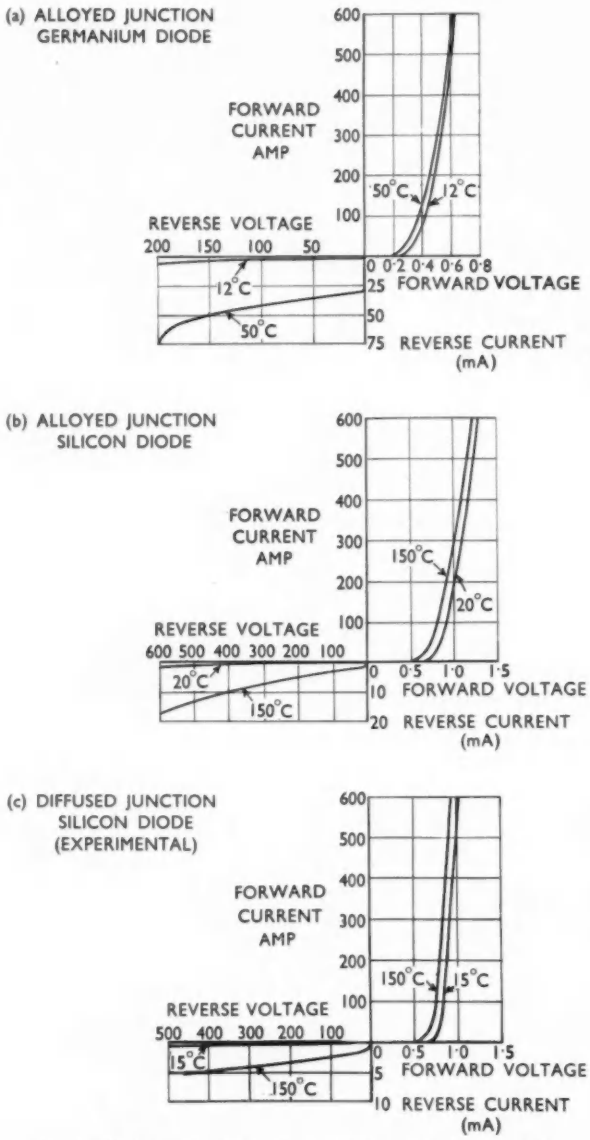


*Fig. 8.—Typical instantaneous forward and reverse characteristics of high-power germanium and silicon diodes (junction areas 2 cm²).*

**Design Principles for Germanium and Silicon Rectifier Equipments.**

During the last few years much experience has been gained in the design of germanium and silicon power rectifier equipments[30-56]. It is estimated that today between 500 MW and 1000 MW of these rectifiers are in use in the western world—and the total is increasing rapidly. For these equipments to operate successfully, effective protective systems must be incorporated. These systems, in addition to performing functions necessary in all rectifier equipments (e.g. protection of transformers and busbars under fault conditions) must adequately safeguard the diodes. For this there are three essential requirements :

(*i*) the junctions in the diodes must not be allowed to get too hot ;

(*ii*) reverse voltages in excess of the breakdown voltage must not be applied, even momentarily ;

(*iii*) in some circuits and for some diodes, the rate of rise of reverse voltage immediately after forward conduction must be restricted.

*The Influence of Overload and Fault Conditions on the Selection of Junction Operating Temperatures and Currents*[33, 37, 39, 40, 43, 44, 47, 49, 53, 54, 55, 57].

It is a characteristic of germanium and silicon diodes that current densities in the junctions are high and that the masses and thermal capacities of the junction regions are very low. Consequently, if a fault current amounting to several times the normal current flows through a diode for a short time, a large amount of additional energy is dissipated in a region of low thermal capacity and the junction temperature rises rapidly.

This effect is illustrated in fig. 11, where the temperature dependence of the reverse current is used as a means of measuring the junction temperature in a high-power germanium diode. The diode is operated as a half-wave rectifier and during alternate half-cycles, when no forward current flows, a fixed reverse voltage is applied. The junction temperature corresponding to the observed reverse current is

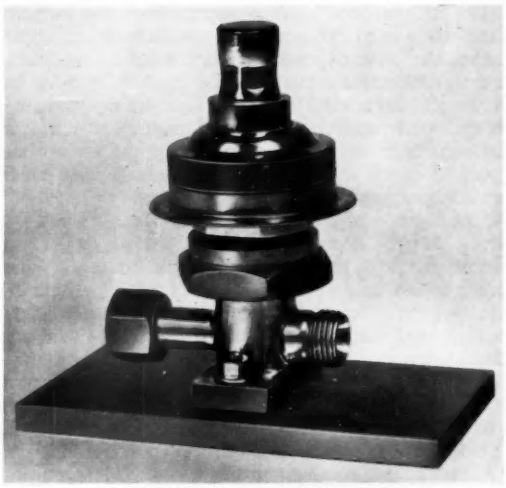

*Fig. 9.—Water-cooled silicon diode.*

determined from a separate oven calibration of the diode. At the initial part of the trace, the junction has already reached thermal equilibrium at a current of 150 A mean. When an overload current of 2500 A peak (i.e. about five times the normal current) flows, there is a rapid increase in junction temperature. When the current reverts to normal, the junction temperature quickly falls again.

Because the junction in a diode must not be allowed to get too hot under fault conditions, its temperature during normal operation must be far enough below the danger level to allow an adequate safety margin for the additional heating produced by the excess current. Thus the maximum permissible temperature during normal operation (and hence the current rating at

TABLE 1.

Overall thermal impedance, junction to air, for an alloyed-junction silicon diode (junction area 2 $cm^2$) mounted on various extruded aluminium fins.

| Overall size and surface area of fin | | Overall thermal impedance, junction to air, °C per watt (measured at 60° C junction temperature rise) | |
|---|---|---|---|
| Total space occupied by finned diode $in^3$ | Surface area of fin $in^2$ | Natural Cooling | Forced-air cooling (air speed 1000 ft/min) |
| 19 | 56 | — | 0·63 |
| 38 | 116 | — | 0·57 |
| 54 | 130 | 1·3 | 0·55 |
| 121 | 292 | 1·1 | — |

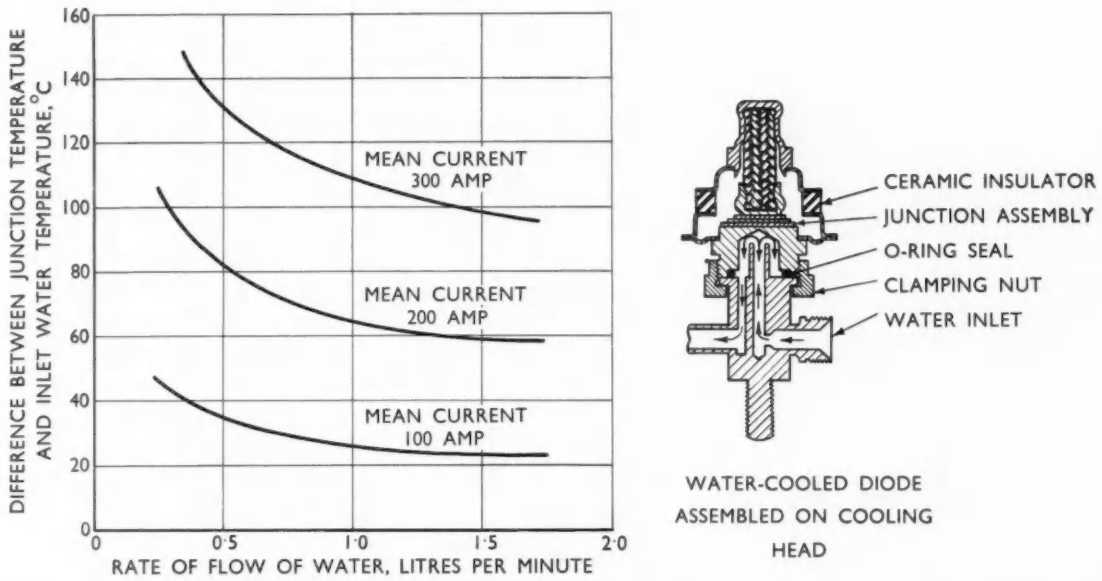


*Fig. 10.—Junction temperature rise in a water-cooled alloyed-junction silicon diode (junction area 2 $cm^2$).*

which a diode can be used) is often dictated by the nature of the overload and fault conditions and the characteristics of the protective devices.

In all equipments it is necessary to protect against faults resulting from failure of a diode. Almost invariably, a diode becomes short-circuited if it fails, with the result that good diodes elsewhere in the circuit are connected directly across the secondary lines of the rectifier transformer. If the transformer

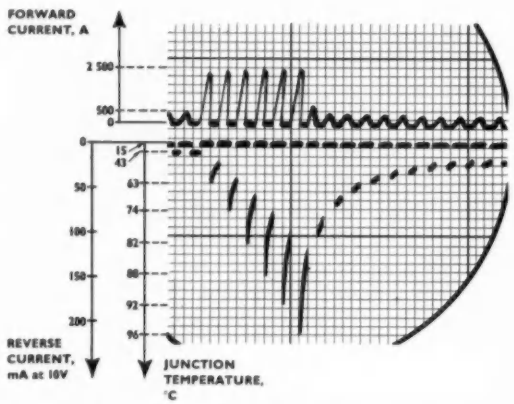


*Fig. 11.—Oscillogram showing junction temperature rise under overload conditions in a water-cooled alloyed-junction germanium diode (junction area 2 cm²). Note the fall in junction temperature during the half-cycle periods when the diode is not passing forward current.*

impedance is sufficiently high, these diodes may be able to withstand the fault current until the fault is cleared by operation of fuses or circuit-breakers in the transformer primary circuit. In general, it is impracticable to provide sufficient impedance and it is usual to connect a special fast-acting current-limiting fuse[57-60] in series with each diode (or string of series-connected diodes in higher voltage equipments) as shown in fig. 12. In this circuit, as in most industrial rectifier equipments, there are several parallel-connected paths in each arm. The fault current, on failure of a diode, is shared among all the parallel-connected diodes (and their fuses) in another arm, and the fault is cleared by the fuse in series with the defective diode. Provided there are sufficient parallel paths (usually three or more) in each arm, the fuses in series with good diodes which carry a share of the fault current are unaffected. By providing more than the bare minimum number of diodes, it is possible to avoid interrupting the d.c. supply on failure of a diode. Special auxiliary fuses connected in parallel with the main fuses, or small current transformers in series with them, can be used to provide visual indication of diode failure.

In circuits where groups of diodes are connected in parallel, the forward volt-drop is the same for all diodes in a group. To avoid non-uniform current distribution and consequent overheating of some diodes, the forward characteristics must be matched, or devices to enforce current sharing[40, 49, 61] must be included; otherwise, substantial derating may be necessary. In addition, the fuses must be of uniform resistance and care must be taken with the busbar layout to ensure that all diodes in a group have equal series impedance.

To protect against overloads and short-circuits on the d.c. side of the rectifier it is undesirable to have to rely on fuses in the individual diode circuits. The choice of protective system is influenced by the probable frequency and severity of faults. An a.c. circuit-breaker used in conjunction with a high reactance transformer is often sufficient but in some circumstances (especially when severe faults can occur and when other power sources are operated in parallel with the rectifier) it may be necessary to provide a high-speed d.c. circuit-breaker as well.

A fast-acting short-circuiting switch is sometimes used as an alternative to the d.c. circuit-breaker, or to both circuit-breaker and diode fuses[47]. On occurrence of a d.c. fault, or a diode fault, this short-circuits the output terminals of the rectifier transformer within one or two milliseconds, thus quickly transferring the fault from the rectifier to the transformer where it is cleared more slowly (but in a time acceptable for transformer protection) by the a.c. circuit-breaker.

To ensure that all the protective devices fulfil their intended functions, their operating characteristics must be properly co-ordinated and related to the overload capacity of the diodes[44, 53, 57]. Typical overload curves for a forced-air-cooled finned silicon diode are given in fig. 13. They show alternative overload ratings appropriate to basic ratings of 100 A and 125 A.

When attempting to increase the current rating of a diode by improving the cooling of the junction, it is necessary to do more than find ways of maintaining the same junction temperature at the higher current. For the diode to be equally useful, it must have the same overload capacity (expressed as ratio of permissible fault current to rated current) as before. This means that it must be able to withstand higher fault currents and therefore that its junction temperature during normal operation must be lower.

At the present time, the working current densities in germanium and silicon diodes under normal running conditions in rectifier equipments (as distinct from absolute maximum values, with no overload capacity in hand) generally lie within the range 30-90 A/cm².

*The Influence of Transient Voltages on the Selection of Working Reverse Voltages.*

In all rectifier equipments, transient voltages in excess of the normal working voltage are liable to be produced during switching operations and under certain other conditions[33, 37, 47, 55, 62, 63, 64]. These transients (as distinct from overvoltages fed back by regenerative loads, which call for special treatment) have a limited energy content. They seldom cause trouble in selenium rectifier equipments where the

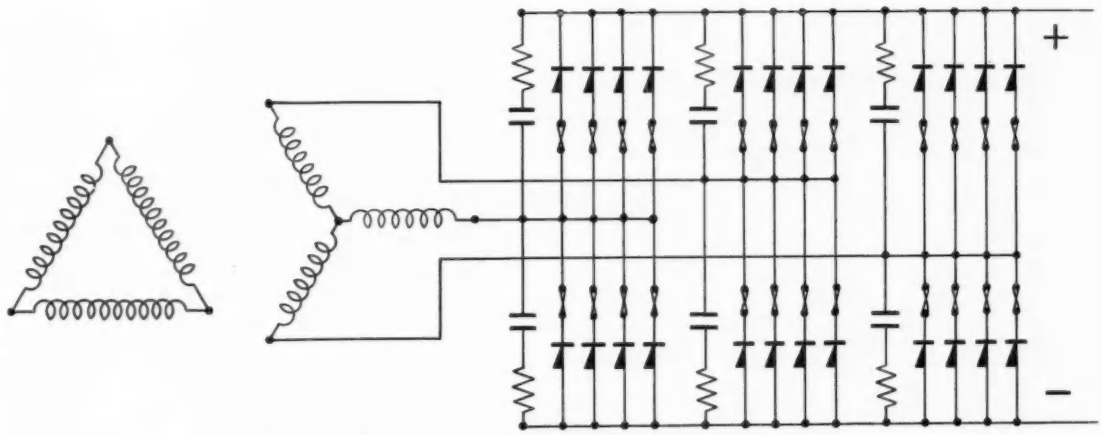


*Fig. 12.—Rectifier circuit, showing protective fuses, capacitors and resistors.*

high plate capacitance and low reverse resistance, which slow the rate of rise of voltage and limit the peak voltage, are important features.

In germanium and silicon rectifiers, diode capacitances are very much lower and reverse resistances higher. The diodes themselves (particularly silicon diodes) do little to store or dissipate the transient energy and in the absence of protective devices, voltages could rise to values many times the normal working recurrent peak inverse voltage. Diodes break down instantaneously if subjected to excessive reverse voltages and it is therefore essential to protect them.

In high-power rectifier equipments, the main sources of transients are :

(*i*) Opening and closing of the primary circuit of the rectifier transformer.

Conditions during opening of the primary circuit are particularly severe when there is no load on the rectifier. The sudden collapse of the transformer magnetizing current and magnetic flux give rise to a steep-fronted high-voltage pulse in the secondary. On closing the primary circuit, transients can be generated as a result of the sudden inrush of current and also (with step-down transformers) because of capacitive coupling between primary and secondary. All these effects are aggravated by contact bounce in the switching device.

(*ii*) Opening of a circuit-breaker in the rectifier load circuit.

Transients caused in this way are most serious when the breaker opens under overload or short-circuit conditions.

(*iii*) Blowing of fuses in the diode circuits.

When a diode fails and the fuse in series with it suddenly interrupts a fault current, a high voltage is liable to be developed across the fuse and across diodes in parallel with the faulty one.

(*iv*) Disturbances entering via the incoming supply —e.g. lightning surges.

(*v*) ' Hole storage ' effects in diodes.

During commutation, at the changeover from forward conduction through a diode to reverse blocking, there is a finite time interval—the ' hole storage ' period—during which current carriers are swept from the junction region[33, 37, 63, 65]. If carriers are still present when the

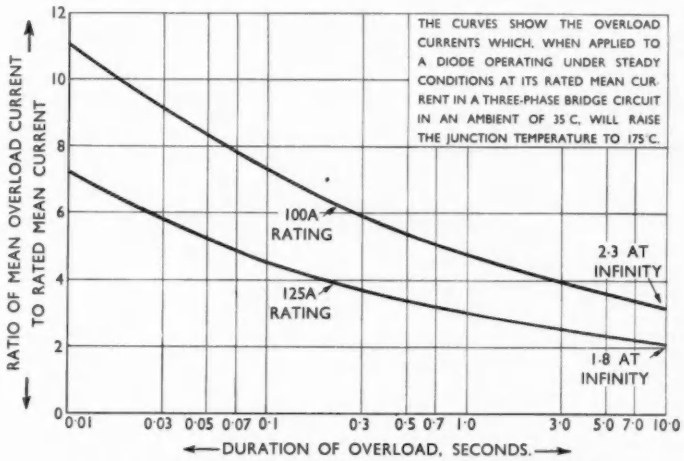


*Fig. 13.—Overload performance of a forced-air-cooled alloyed-junction silicon diode (junction area 2 cm²) mounted on the second of the fins listed in Table 1.*

reverse voltage begins to rise, a substantial reverse current can flow and when the diode recovers its blocking characteristic this current will fall rapidly to zero. This sudden interruption of current gives rise to a voltage pulse. With some diodes and in some circuits, ' hole storage ' pulses can be troublesome.

The methods of safeguarding germanium and silicon diodes against transients involve firstly, taking precautions to suppress the transients, and secondly, allowing an adequate safety margin between the maximum peak inverse voltage the diodes will withstand and the recurrent peak inverse voltage at which they are operated in rectifier equipments.

In practice, transients are suppressed by connecting non-linear resistors, or more usually capacitors, in appropriate positions in the circuits. In fig. 12, separate capacitors are shown connected across each arm of a three-phase bridge. Alternatively, they may be connected across the a.c. feeders to the rectifier ; or part of the capacitance (for suppressing transformer switching transients) may be transferred to the primary side of the transformer—an arrangement which offers advantages for high-power low-voltage rectifiers because it enables smaller capacitors to be used. Usually, resistors are connected in series with the capacitors to damp oscillations. Current-limiting fuses specially designed for use with germanium and silicon diodes, and having limited arc voltages, are now available[57-60].

The second safety factor—the margin between maximum and operating peak inverse voltages—guards against trouble at the suppressed values of the transients. Its magnitude depends on circuit conditions ; typically, diodes are operated at a recurrent peak inverse voltage which is between one-third and a half of their rated maximum peak inverse voltage. The rated maximum p.i.v. is itself determined from consideration of three factors—the reverse breakdown voltage of the junction, the need to guard against ' thermal runaway ', and the need for long-term stability. At a given forward current, a particular reverse voltage will cause thermal runaway[37, 39] if a curve relating total power generation in the junction to junction temperature fails to intersect a curve relating the power which can be removed from the junction (by whatever cooling means is in use) to junction temperature.

Reverse voltage ratings of germanium and silicon diodes are being steadily improved. For the largest diodes, present working recurrent peak inverse voltages (as distinct from absolute maximum p.i.v. ratings) usually range up to 100 V for germanium and 200 V for silicon. Higher working voltages (up to 250 V for germanium and 550 V for silicon) are possible with rather smaller diodes and there is no doubt that the next few years will bring further improvements.

For voltages which are higher than can be handled with single diodes, strings of series-connected diodes are used. Since the reverse current is the same through all diodes in a string, there is a measure of self-protection against runaway and some manufacturers permit higher working reverse voltages per diode. Small capacitors are usually connected across the individual diodes in a series string. These serve two purposes. Firstly they distribute steep-fronted transient voltages reasonably uniformly across the individual diodes. In the absence of capacitors, these transients would tend to develop preferentially across the diodes at the end of the string where capacitance to earth was least. Secondly, with diodes for which carrier storage effects during commutation would otherwise be troublesome, by reducing the rate at which the reverse voltage rises, they obviate the risk of a dangerously high voltage being developed across the first diode to recover its blocking characteristic. Some manufacturers fit voltage-equalizing resistors in addition to capacitors across the individual diodes.

### Characteristics of Germanium and Silicon Rectifier Equipments.

Although the diodes in germanium and silicon rectifier equipments require careful protection, the equipments themselves are at least as well able to withstand severe treatment as any other type of rectifier. The problems of diode protection are problems for the equipment designer, not problems for the user—and fortunately the solutions are known.

The advantages of germanium and silicon rectifiers over other types of conversion equipment arise from their high efficiency, compactness, simplicity, reliability, good regulation and low maintenance requirements, and (in comparison with selenium) their freedom from ageing and (in comparison with mercury arc) their ability to operate without difficulty in low-temperature situations.

Of the two, germanium is the more efficient at low voltages (up to the voltage at which it becomes necessary to connect two germanium diodes in series). At rather higher voltages, where there are the alternatives of using one silicon diode or two germanium diodes in series, there is little to choose in efficiency but the silicon equipment requires only half as many diodes and is more compact. For still higher voltages (above the ' low voltage range ' now under consideration) improvements in silicon are likely to make it the more efficient as well as the more compact.

Inherently, because of the low forward volt-drops in the diodes, germanium and silicon rectifier equipments are capable of having very good regulation. To obtain the best performance, the transformers feeding the rectifiers must have low commutating reactance. Difficulties then arise with protection, because short-circuit currents are high. The difficulties can be overcome by providing sufficient numbers of diodes, and in practice a balance is struck between the desire for the best regulation on the one hand and the desire to use fewer diodes (with consequent saving in cost) on the other.

There is no problem in operating germanium or silicon rectifiers in ambients at normal industrial temperatures (i.e. about 35° C maximum). Because there is a lower margin, with germanium rectifiers, between junction temperature and ambient tempera-

ture, they must be derated more severely than silicon rectifiers if required to operate at higher temperatures.

A water-cooled germanium rectifier rated at 2200 A, 55 V, 121 kW is shown in fig. 14. It contains 48 diodes of an earlier pattern than those in fig. 6, connected in a three-phase full-wave bridge circuit. The usual safe-

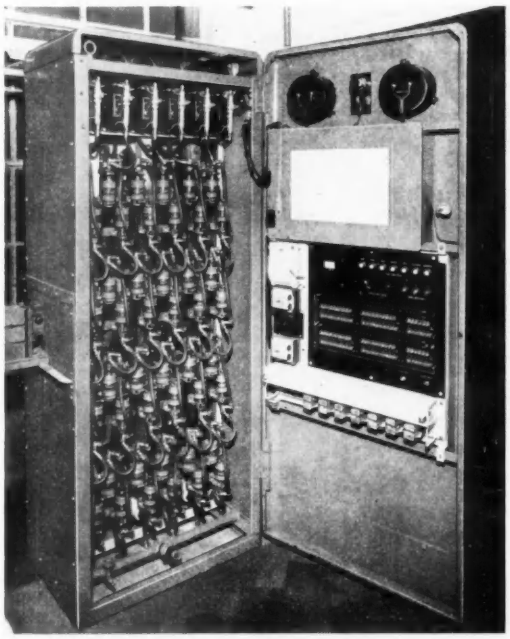

*Fig. 14.—Water-cooled germanium rectifier with d.c. output 2200 A 55 V 121 kW.*

guards (water flow relays, water thermostat, fuses, diode failure indicators and automatic trips) are incorporated. The total water requirement, for cooling diodes, busbars and the non-linear resistors used for suppressing transient voltages, is only 6 litres (1·3 gallons) per minute. The rectifier has replaced a motor-generator set and operates continuously, providing power to a battery of electrolytic cells which are used for producing hydrogen. Because of the higher efficiency of the rectifier, there is a saving in power costs (in comparison with those for an efficient modern motor-generator set) of about £1000 per annum. In addition, maintenance costs are considerably lower.

A water-cooled silicon rectifier, also for continuous electrolytic duty, and rated at 2200 A, 30 V, 66 kW is illustrated in fig. 15. This rectifier is sufficiently compact (42 in. × 12 in. × 12 in., excluding projecting busbars) to enable the usual floor-standing cubicle to be dispensed with ; it is designed for direct mounting on its associated transformer—a procedure which can also be adopted for equipments of considerably higher rating.

This feature of extreme compactness is leading to the opening up of new fields of application for rectifiers—for example in the construction of brushless alternators, where silicon diodes mounted on the rotor and capable of withstanding high-speed rotation provide the d.c. excitation current[66, 67].

### Silicon Controlled Rectifiers.

Control of d.c. output voltage from the rectifiers in figs. 14 and 15 is obtained by means of continuously variable transformers at the input sides of the rectifiers. It is clear, from the course now being taken by developments in solid-state devices (particularly silicon *p-n-p-n* structures), that before long it will be possible to obtain effective control of output voltage in rectifiers of substantial power rating without using variable transformers, induction regulators or similar equipment. Moreover, it will be possible to obtain much faster response than these conventional regulators can provide. In the three-junction *p-n-p-n* silicon controlled rectifier[68-74], forward conduction is initiated by application of a signal to a ' gate ' electrode connected to the internal *p*-region. In its electrical characteristics, the device resembles the thyratron but its mechanism of triggering and its triggering circuits are different, and when in the conducting state it has the low forward volt-drop of a silicon diode. In a rectifier circuit incorporating controlled rectifiers, control of d.c. output voltage is obtained by adjustment of the phase of the triggering signals to the gate electrodes.

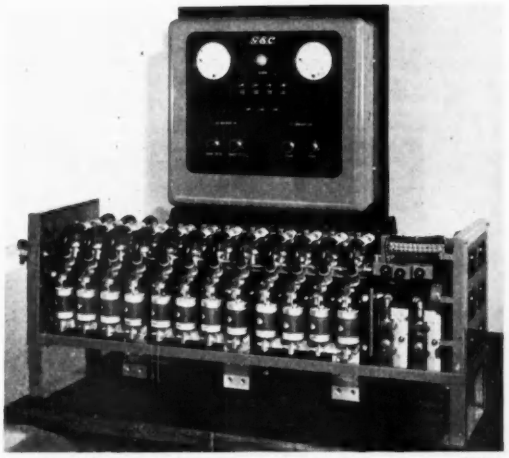

*Fig. 15.—Water-cooled silicon rectifier (rated d.c. output 2200 A 30 V 66 kW) with its separate control panel.*

At present, silicon controlled rectifiers with current ratings up to 10 A and p.i.v. ratings up to 200-300 V (all absolute maximum values) are just becoming available in this country. With further development, these ranges will be extended and controlled rectifiers are likely to be used extensively in the future in variable d.c. supplies (for example for motor speed

control) and in a variety of other switching and control applications. The rectifiers can be used for inversion and frequency conversion and there are potentially important applications in the provision of constant frequency supplies from variable-speed alternators.

**FACTORS INFLUENCING THE CHOICE OF RECTIFIER FOR LOW-VOLTAGE WORK.**

There is no single general answer to the question 'Which type of rectifier is best for applications in the low voltage field?' Much depends on the user's requirements—on the voltage in which he is interested, the nature of the overload conditions, and on the relative importance to him of initial cost, efficiency, compactness, proneness to ageing, and good regulation (factors which sometimes conflict with one another).

At the lowest voltages, germanium rectifiers are the most efficient and at all voltages, germanium and silicon are more efficient than selenium. The efficiency advantages of germanium and silicon are greatest when they are used at their full voltage ratings, or at multiples of these voltages; under these conditions, several series-connected selenium plates (with losses correspondingly greater than for a single plate) fulfil the same functions as single germanium and silicon diodes. For similar reasons, germanium and silicon rectifiers are most attractive in initial cost when the diodes are operated at their full voltages.

The monetary value of the increased efficiency is shown in fig. 16. At 150 V, for example, and for a rectifier which operates continuously, the annual saving through using germanium or silicon rather than selenium is nearly £500 per 1000 A of d.c. output (assuming an electricity cost of 1d. per kWh). For a rectifier operating 42 hours a week, the savings would be one quarter of the amounts shown.

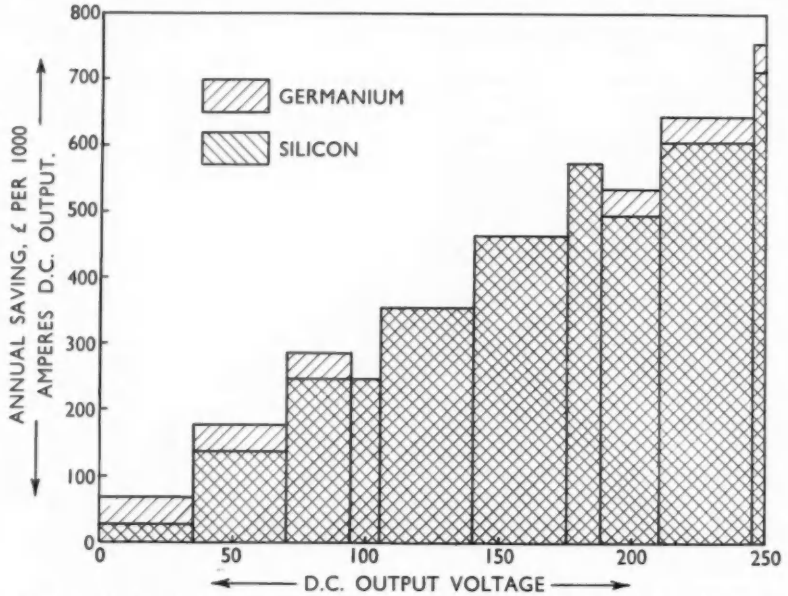


*Fig. 16.—Reduction in power costs through using germanium or silicon rectifiers rather than selenium rectifiers. The figures are calculated for the three-phase bridge connexion, with the rectifier operating continuously and with an electricity cost of 1d. per kWh. Rectifier characteristics are taken as:*

*Selenium plate: 40 V working p.i.v., 1·5 V forward drop.*
*Germanium diode: 100 V working p.i.v., 0·55 V forward drop.*
*Silicon diode: 200 V working p.i.v., 1·1 V forward drop.*

The savings in fig. 16 are calculated for rectifiers operating in the three-phase bridge connexion. At the lowest voltages (up to 17 V) higher efficiencies are obtainable with all three types of rectifier by using the six-phase connexion shown in fig. 3(*a*). The saving, through using germanium or silicon rather than selenium, is then reduced to half the value shown. By using this connexion with germanium and silicon at still higher voltages, the savings are rather greater than shown in fig. 16; against this, the six-phase connexion necessitates a more costly transformer.

One conclusion which can be drawn from fig. 16 is that the case for preferring germanium or silicon to selenium is least strong in comparatively low-power and low-voltage applications, particularly when the

rectifier is not required to operate continuously. In this range, the rather greater simplicity of the selenium rectifier (which results from the relative insensitivity of the selenium plate to overloads and the fact that series-connexion of plates is unnecessary) is often decisive. At higher voltages, and especially when the rectifier is operated continuously (as often happens in electrochemical applications), the savings through using germanium or silicon are substantial.

In the low-voltage field, the mercury arc rectifier is used only at voltages at the upper end of the voltage range, i.e. at 200-250 V. The multi-anode rectifier then has about the same efficiency as the selenium rectifier, and germanium and silicon rectifiers offer the same advantages over it in running costs as is indicated in fig. 16. Although the ' Com-Pak ' rectifier and certain other single-anode rectifiers have lower volt-drops than the multi-anode type, they are still substantially less efficient at 200-250 V than germanium or silicon rectifiers. Moreover, all the mercury arc rectifiers require more expensive transformers and more auxiliary devices (because of the need for firing circuits) than the other rectifiers. Except when the grid-control feature of the mercury arc rectifier is required, or when efficiency is of little importance, germanium or silicon rectifiers are likely to be preferred. As silicon controlled rectifiers of higher ratings become available and as experience is gained with them, they are likely to compete increasingly with the grid-controlled mercury arc rectifier in applications where rapid control of voltage is required.

The contact rectifier[75-83] is used mainly at currents of 10 000 A or more in large-scale electro-chemical and electro-metallurgical work where efficiency and reliability are of paramount importance. Initially, it was designed for voltages of 100-400 V and in this range, its advantage in efficiency over motor-generators, rotary convertors and mercury arc rectifiers made it very attractive. Many large installations (mostly overseas) have operated successfully for several years. The main disadvantages of the rectifier are that it has moving contacts and other mechanical parts which require maintenance and that supply system disturbances, by upsetting synchronism between the supply and the contact mechanism, are liable to cause interruptions. With the introduction of germanium and silicon rectifiers which have efficiencies closely comparable with its own and which are more compact, have few if any moving parts and are virtually free from maintenance problems, the position of the contact rectifier requires re-examination. Two years ago, it was claimed[82] that although contact rectifiers were more costly than semiconductor rectifiers at the lower ratings, they had advantages when large outputs were required (a single rectifier with six working contacts could provide 20 000 A 350 V d.c.) and were cheaper. Since then, the rapid progress with germanium and silicon rectifiers has continued and many very large installations are now in operation or under construction. There can be little doubt that the future will bring further progress with semiconductor rectifiers and that improvements in diode performance and in the performance of controlled rectifiers will lead to the consolidation of present applications and the opening up of new ones.

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# TECHNICAL LITERATURE

*A digest of recent articles and papers by members of the G.E.C. and its associated companies*

### A SIMPLIFIED APPROXIMATE THEORY OF PASSIVE REFLECTOR MICROWAVE AERIAL SYSTEMS (772).*

**By R. G. Medhurst (Research Laboratories).**

*Electronic and Radio Engineer, Vol.* 36, *No.* 12, *pp.* 443-449, *December*, 1959.

The performance of a few special types of passive reflector aerial systems have been evaluated by methods involving considerable numerical computation. In this article it is shown that certain plausible assumptions concerning the near field of the primary aerial lead to quite a simple theoretical treatment applicable to a variety of shapes of reflector.

### THE NON-STOICHIOMETRY OF TANTALUM CARBIDE (788).*

**By D. A. Robins (Research Laboratories).**

*The Physical Chemistry of Metallic Solutions and Intermetallic Compounds. Proceedings of a Symposium held at the National Physical Laboratory on June* 4, 5 *and* 6, 1958.

From the results of X-ray and chemical analysis on the *NaCl* type tantalum carbide prepared either by gaseous carburization of metal filaments or by reaction of tantalum and carbon in a molten bath of iron or aluminium, it is shown that the maximum percentage of carbon which can exist in tantalum carbide corresponds to a composition of approximately $TaC_{0.96}$ and that the limiting composition is independent of both the method of preparation and the temperature of preparation within the range 1500° C to 2500° C.

### ELECTRON TRAPS IN PHOTOCONDUCTING CADMIUM SULPHIDE CRYSTALS (791).*

**By J. Woods and D. A. Wright (Research Laboratories).**

*Solid State Physics in Electronics and Telecommunications. Proceedings of an International Conference held in Brussels, June* 2-7, 1958.

The method of preparation of cadmium sulphide affects spectral sensitivity, speed of response, and the variation of photocurrent with temperature and with intensity of illumination. In the work described, these properties have been studied between —170° C and +120° C. In addition, the electron trap distribution has been determined by study of the ' thermally stimulated current ' and this distribution has been correlated with speed of response and variation of photocurrent with temperature. Five major trapping levels have been observed, and their identification with impurity and vacancy levels is discussed.

### HIGH FORWARD CURRENT FLOW IN JUNCTION DIODES (793).*

**By A. K. Jonscher (Research Laboratories).**

*Solid State Physics in Electronics and Telecommunications. Proceedings of an International Conference held in Brussels, June* 2-7, 1958.

The theory of injection-limited flow and high-injection level flow in junction diodes is outlined and some experimental results obtained on various junction diodes are described. These results in turn lead to a new approach to the problem of current flow at high-injection levels.

### BISMUTH TELLURIDE AND ITS THERMOELECTRIC APPLICATIONS (797).*

**By D. A. Wright (Research Laboratories).**

*Solid State Physics in Electronics and Telecommunications. Proceedings of an International Conference held in Brussels, June* 2-7, 1958.

The theory of thermojunctions for refrigeration is outlined and the properties of bismuth telluride and its alloys and their application to thermoelectric cooling and thermoelectric generation are described.

### POWER TRANSISTOR DESIGN FOR HIGH CURRENT OPERATION (800).*

**By R. D. Knott, M. R. P. Young and I. D. Colson (Research Laboratories).**

*Solid State Physics in Electronics and Telecommunications. Proceedings of an International Conference held in Brussels, June* 2-7, 1958.

Some design features of germanium *p-n-p* power transistors leading to improved emitter efficiency and low values of collector-emitter voltage when the transistor is current-saturated and of base-emitter input voltage are discussed.

### THE CONTAMINATION OF SILICON BY THE CRUCIBLE (808).*

**By S. E. Bradshaw (Research Laboratories).**

*Solid State Physics in Electronics and Telecommunications. Proceedings of an International Conference held in Brussels, June* 2-7, 1958.

The Czochralski (or ' Pulling ') process for preparing single crystals of silicon is well known, and where a crucible is employed it is commonly fabricated from high-purity silica. The purpose of this paper is to consider the extent to which the silica crucible can affect the concentration and distribution of impurity in a single crystal of silicon when evaporation and segregation of impurities have occurred at some stage in its growth.

### ANALYTICAL PROBLEMS IN THE ELECTRICAL INDUSTRY: THE APPLICATION OF MICRO-TECHNIQUES (819).*

**By R. C. Chirnside (Research Laboratories).**

*Proceedings of the International Symposium on Microchemistry, held in Birmingham, August*, 1958.

Selected examples of the analysis of small quantities in the electrical industry are given. These include the study of the reaction of magnesium and beryllium with carbon dioxide, the depth of penetration of carbon into zirconium, the effect of carbon monoxide and dioxide mixtures on iron, the determination of very small quantities of cobalt in steel, boron in carbon and impurities in carbon dioxide. These illustrate the wide range of techniques used, including not only chemical methods but also spectrographic, polarographic, absorptiometric and conductimetric methods, and X-ray diffraction.

### STRUCTURE TRANSFORMATIONS EFFECTED BY THE DEHYDRATION OF DIASPORE, GOETHITE AND DELTA FERRIC OXIDE (847).*

**By M. H. Francombe and H. P. Rooksby (Research Laboratories).**

*Clay Minerals Bulletin, Vol.* 4, *No.* 21, *pp.* 1-14, *August*, 1959.

X-ray powder diffraction studies have been made of the structure changes which occur on dehydrating the minerals

diaspore and goethite, and also the synthetically-prepared '$\delta$-$Fe_2O_3$.' For diaspore and goethite the changes are interpreted in terms of *superstructures* referred to a hexagonal, anion lattice sub-unit which is common to both the $\alpha$-type oxyhydroxides and the anhydrous corundum or hematite structures. The ferromagnetic $\delta$ oxide, obtained by rapid oxidation of ferrous hydroxide, is shown to be a true oxyhydroxide of the form *FeOOH*.

### THERMO-ELECTRIC REFRIGERATION AS AN AID TO TRANSISTOR OPERATION (852).*

**By H. J. Goldsmid and R. A. Hilbourne (Research Laboratories).**

*British Communications and Electronics, Vol.* 7, *No.* 1, *pp.* 26-30, 1960.

At present the continuous operation of germanium transistors above a temperature in the region of 100° C is impossible. They could only be used at higher ambient temperatures if some means of refrigeration were provided. In this case, cooling by means of the Peltier effect should prove more convenient than any other form of refrigeration. Silicon transistors are generally inferior to germanium transistors for high-frequency operation but they have the advantage of an upper temperature limit of about 200° C. For use at still higher ambient temperatures it would be necessary to employ different semiconductor materials, or alternatively, to refrigerate silicon devices. Again, thermoelectric refrigeration could be employed.

### TEMPERATURE EFFECTS IN FLAME PHOTOMETRY (867).*

**By R. C. Chirnside and J. E. Still (Research Laboratories).**

*XV Congresso Internacional de Quimica pura e Aplicada Lisboa*, 1958.

Some anomalous results obtained during the determination of calcium by means of flame photometry led the authors to investigate various aspects of this valuable and rapidly developing technique. Attention was directed in the first instance to the effects of solution temperature on the emission from the flame, and subsequently to the effect of variation in flame conditions.

### A METHOD FOR ACCURATE DESIGN OF A BROAD-BAND MULTI-BRANCH WAVEGUIDE COUPLER (869).*

**By K. G. Patterson (Research Laboratories).**

*IRE Transactions on Microwave Theory and Techniques, Vol. MTT-7, No.* 4, *October*, 1959.

A new approach is made to the problem of tapering the branch impedances for broad-band performance. A taper is proposed, which, for a 3-*db* branch coupler, is shown to give much better results in theory and practice than the currently used binomial taper. Also, simple expressions are developed which enable the effects of waveguide junction discontinuities to be adequately corrected, thus allowing a greater accuracy in design to be achieved than was hitherto possible.

### THE EFFECTS OF HEAT TREATMENTS ON THE THERMAL EXPANSIONS OF SOME BOROSILICATE GLASSES AND IRON-NICKEL-COBALT ALLOYS AND THEIR SIGNIFICANCE IN THE BEHAVIOUR OF GLASS TO METAL SEALS (875).*

**By L. F. Oldfield (Research Laboratories).**

*Glastechnische Berichte Sonderband: V. Internationaler Glaskongress* 32*K*, *No. V*, 1959.

Practical experience has shown that when certain combinations of glass and metal are sealed together to make joints giving, initially, entirely satisfactory performances, their subsequent baking at elevated temperatures for extended periods results in seal fracture. Studies of the influence of temperature and time on the thermal expansion properties of various glasses and alloys, and on the development of the stresses in the seals, have established that baking for outgassing purposes should not be maintained for prolonged periods within the temperature interval, approximately 300° C to 450° C.

### STUDY OF CADMIUM SULPHIDE CRYSTALS GROWN FROM THE VAPOUR PHASE IN A STREAM OF ARGON (876).*

**By J. Woods (Research Laboratories).**

*British Journal of Applied Physics, Vol.* 10, *pp.* 529-533, *December*, 1959.

Crystals of cadmium sulphide have been grown by reacting a stream of argon containing cadmium vapour with a stream of hydrogen sulphide. The variations in crystal habit which occur are very similar to those reported for ice crystals by Hallett and Mason. Growth features were studied using a metallurgical microscope. Although growth occurs in layers, spirals were only observed on rare occasions. The evidence indicates that ordinary two-dimensional nucleation over a plateau is more common, and is affected by the impurities added. Nucleation also occurs at sites on the edge of a crystal face or at the apexes of re-entrant angles between growth steps from neighbouring sources. Various types of cavity have also been observed in the volume of some crystals, and possible methods of formation are discussed.

### THE SELECTION OF BASIC BRICKS FOR GLASS TANK REGENERATORS (877).*

**By T. S. Busby (Research Laboratories).**

*Glastechnische Berichte Sonderband: V. Internationaler Glaskongress* 32*K*, *No. IV*, 1959.

Samples of commercial basic bricks including magnesite, magnesite-spinel, chrome-magnesite, magnesite-chrome and forsterite have been tested for porosity, thermal expansion, thermal shock, creep under tensile loading at 1400° C, reaction with batch making chemicals at 1400° C and changes caused by repeated oxidation and reduction at 1400° C. It was shown that basic bricks are weak under tensile loading and that those highest in magnesia content were the most resistant to alkali attack. Bricks containing chromite expanded and became very friable under repeated oxidation and reduction. The thermal shock test showed that while basic bricks will withstand +50 cycles between 1000° C and room temperature, they crack after only 1-7 cycles from 1400 to 900° C.

### THE CORROSION OF SUPERSTRUCTURE AND REGENERATOR REFRACTORIES BY GLASS BATCH MATERIALS (878).*

**By T. S. Busby (Research Laboratories).**

*Glass Technology, Vol.* 1, *No.* 1, *pp.* 11-16, *February*, 1960.

Samples of twenty refractory materials have been sprayed with $K_2CO_3$, $Pb_3O_4$, and $Na_2SO_4$ at 1400° C. While the corrosion was related to the chemical composition of the samples, it has been shown that the porosity of the sample had an important influence on the result.

### COPPER AND TIN-ACTIVATED HALOPHOSPHATE PHOSPHORS (880).*

**By B. E. Hunt and A. H. McKeag (Research Laboratories).**

*Journal of the Electrochemical Society, Vol.* 106, *No*, 12. *December*, 1959.

New copper- and tin-activated halophosphate phosphors, fired in mildly reducing atmospheres and of potential practical importance, are described. The include copper- and tin-activated barium chlorophosphates with good thermal characteristics. Copper-activated barium chlorophosphate shows a moderate red fluorescence at ambient temperatures, under long u.v. excitation, which becomes brighter at higher temperatures due to a marked color shift toward the yellow. The same matrix, activated with tin, shows a strong pale green fluorescence at ambient temperatures when excited by 2537A radiation which is shifted toward the blue at elevated temperatures.

### APPLICATION OF THE RELAXATION METHOD TO THE SOLUTION OF SPACE CHARGE PROBLEMS (882).*

**By P. A. Lindsay (Research Laboratories).**

*Journal of Electronics and Control, Vol. 6, No. 5, p. 415, May, 1959.*

A numerical method of solution of the space charge equation in one dimension is described. The advantages of the method are its speed and flexibility. It can be applied whenever, on physical grounds, it is possible to assume that the initial velocity of the electrons is approximately single-valued. The method breaks down whenever this is not so as, for example, is the case in the presence of a virtual cathode when a double-stream flow of electrons exists in part of the interelectrode space.

### LINEAR NETWORK SYNTHESIS: GRAPHICAL METHOD FOR THE APPROXIMATION PROBLEM (883).*

**By G. C. Bown (Research Laboratories).**

*Electronic Technology, Vol. 37, No. 3, pp. 122-126, March, 1960.*

The rational fraction approximation is obtained directly in terms of the pole-zero locations in the *p*-plane by a process of successive approximation. The method differs from other known successive approximation techniques in being purely graphical apart from a final numerical relaxation process. A simple step-by-step account is given of the practical procedure.

### EXPLICIT FORM OF F.M. DISTORTION PRODUCTS WITH WHITE-NOISE MODULATION (886).*

**By R. G. Medhurst (Research Laboratories).**

*I.E.E. Monograph No. 352E.*

When a frequency-modulated wave passes through a network whose phase or amplitude characteristics vary non-linearly with frequency, distortion terms appear as both frequency and amplitude modulation of the output wave. If the characteristics are expressed as power series, these distortion terms appear, to first order, as products of powers of time derivatives of the unwanted frequency modulation. When the frequency modulation may be simulated by a band of random noise (as in multiplex telephony carrying large numbers of channels), the spectra of the distortion products can, in principle, be described by simple algebraic functions of the characteristics (i.e., the minimum and maximum frequencies and the r.m.s. frequency deviation) of the modulating noise band.

### BISMUTH TELLURIDE AND RELATED COMPOUNDS (895).*

**By D. A. Wright (Research Laboratories).**

*Research, Vol. 12, pp. 300-306, August/September, 1959.*

This article summarizes the present knowledge of bismuth telluride and similar compounds, and of alloys formed by substitution of elements from the same coumn of the periodic table. Particular attention is paid to those properties which have a bearing on thermoelectric performance.

### A NEW DESIGN METHOD FOR PHASE-CORRECTED REFLECTORS AT MICROWAVE FREQUENCIES (903).*

**By S. Cornbleet (Research Laboratories).**

*I.E.E. Monograph No. 360E.*

A method is given for the design of a class of wide-angle reflectors in which the aberrations are reduced by coating the reflector surface with a dielectric. At microwave frequencies this dielectric may take the form of an array of metal plates or waveguides and the constraint imposed by this form greatly simplifies the analysis. The path of the feed point is chosen so that only selected rays from it are equally phased. It is then found that both of the reflector's profiles and the path of the feed point can be described by a single parameter.

### MEASUREMENT OF LOW LIGHT LEVELS BY THE PHOTON COUNTING METHOD

**By B. M. Young and L. P. Cooper (Research Laboratories).**

*Transactions of the Illuminating Engineering Society, Vol. 24, No. 1, pp. 46-50, 1959.*

Experiments are described using electron counting techniques for measuring low light levels with photomultipliers. An accuracy of 1% has been achieved in measuring cathode currents of the order of $10^{-15}$ amp. or less with the photomultiplier cooled to —183° C. The luminous flux falling on the cathode of area 2·4 sq in. was c.$10^{-11}$ lumen. At higher levels, the limitations in resolution of the counting equipment available caused 20% loss in counts at cathode currents of $10^{-13}$ to $10^{-14}$ amp.

### HOW LONG WILL A TRANSISTOR LIVE?

**By R. Brewer (Research Laboratories).**

*Wireless World, Vol. 66, No. 3, pp. 108, 109, March, 1960.*

It is natural that with many commercial products we ask the question, ' What is its expected life ? ' Transistors belong to this class of products, and even the non-technical user is beginning to ask, ' How long will a transistor live ? '

This article has been prepared to give guidance in a problem that appears simple, but which is really quite complex, and the basic information is given for a broad, but realistic, approach to the general question of transistor life.

### THE CHARACTERISTICS AND APPLICATIONS OF CORONA STABILIZER TUBES.

**By E. Cohen and R. O. Jenkins (Research Laboratories).**

*Electronic Engineering, Vol. 32, No. 383, January, 1960.*

The corona discharge used for voltage stabilization takes place in hydrogen between a cathode cylinder and an axial wire anode. Apart from thermal effects which become significant in higher voltage tubes the discharge behaves approximately as a constant voltage in series with a resistance. These two parameters depend on the electrode radii and the gas pressure. The characteristics of tubes with subminiature, *B7G* and *B9A* envelopes covering a range of 350 V to 7 kV are given. The tubes are suitable for operation in circuits supplying currents in the range of 0·02 to 1 mA and various applications are outlined.

### COMPOUND SEMICONDUCTORS.

**By D. A. Wright (Research Laboratories).**

*Electronic Engineering, Vol. 31, No. 381, November, 1959.*

This article first discusses the more important parameters governing the behaviour of semiconductors. These considerations are then applied to the various types of semiconducting compound which have so far been studied, and values of the mean parameters are quoted. The usefulness of the materials for different applications is discussed in the light of these figures. In each type of compound, definite trends are observed in the relationship between the semiconducting parameters and other physical properties. These trends are described and their interpretation is indicated.

### RESEARCH IN A LARGE ELECTRICAL ENGINEERING CONCERN.

**By H. K. Cameron (Research Laboratories).**

*Electrical Supervisor, Vol. XXXIX, No. 12, December, 1959.*

The author gives a brief account of the growth and organization of the G.E.C. research laboratory at Wembley, and then selects, by way of example, some of the more outstanding researches which have taken place there, as well as parts of the present programme. It is hoped, by this means, to reveal some of the significant contributions that have come from this laboratory and to indicate the benefits that have come therefrom to the Company, and to the community at large.

## NON-FERROUS METALS IN THE ELECTRICAL INDUSTRY.

**By N. L. Harris (Research Laboratories).**

*Metal Industry, Vol.* 95, *No.* 17, *pp.* 390-395, 4 *December*, 1959.

The author reviews the contribution of the non-ferrous metals industry to development in the electrical industry over the last fifty years, and describes in detail the use of non-ferrous metals for lamps and lighting, electronics, semiconductors, communications, power generation and distribution and nuclear power.

## TRAVELLING-WAVE VALVES: MECHANISMS OF INTERACTION PROCESSES BETWEEN ELECTRONS AND FIELDS

**By C. H. Dix (Research Laboratories).**

*Wireless World, Vol.* 65, *No.* 10, *pp.* 476-481, *November*, 1959.

The object of this article is to describe in a rather more mechanistic way than is usual the interaction processes in the two principal types of travelling-wave valves. By a travelling-wave valve is meant a valve in which two essential features are present :

(1) The valve contains a guiding slow-wave structure which propagates an electromagnetic wave over the frequency range considered at a speed slower than in free space.

(2) There is a continuous interaction between the fields due to this wave and an electron beam.

## A GUIDE TO THE PRACTICAL APPLICATION OF CHEBŸSHEV FUNCTIONS TO THE DESIGN OF MICROWAVE COMPONENTS.

**By R. Levy (Applied Electronics Laboratories, Stanmore).**

*I.E.E. Monograph, No.* 337*E.*

The properties of Chebÿshev functions and their application to the design of several types of microwave components are described.

Formulae giving the broadest possible bandwidth in a given physical length are derived for stepped transformers, stepped twists and multi-element directional couplers. These formulae are intended for practical application by the microwave engineer to the design of actual components, and it is suggested that they should be used rather than the conventional ' binomial ' formulae, which do not give the optimum or simplest design. Microwave band-pass filters with Chebÿshev equal-ripple characteristics are also described.

## EFFECTS OF THE ENERGY OF STRONG PULSES OF IONIC CURRENT ON MICRO-ORGANISMS IN SUSPENSION.

**By B. S. Gossling (Research Laboratories).**

*Nature, Vol.* 184, *pp.* 1881, *December* 5, 1959.

In a general survey of the lethal effects on micro-organisms of passing extremely strong but very brief pulses of current through solutions suspending them comparable attention has been given both to the biological effects and to the physical actions.

## LIGHTING AND ARCHITECTURE.

**By J. M. Waldram (Research Laboratories).**

*Journal of The Institution of Electrical Engineers, Vol.* 6 (*New Series*), *February*, 1960.

Developments in the relation of artificial lighting to architecture could well affect the concept of lighting design and might lead to new professional relationships. In this article the author traces the developments in three stages: decorative lighting equipment which forms part of the furniture of the room, with little change from equipment designed for flame sources ; lighting equipment integrated with architectural features, including false ceilings and indirect lighting ; and a new method known as ' design of the visual field ' in which the lighting installation is so planned as to produce a designed appearance of the whole interior.

* **A limited number of reprints is available of those papers marked with an asterisk. Copies may be obtained on application to the Editor, G.E.C. Journal, Magnet House, Kingsway, W.C.2.**